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AN INVESTIGATION OF THE EFFECTS OF KAOLIN CONTENT ON ELECTRO - OSMOSIS

JAMES A. HARPER

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AN INVESTIGATION OF THE EFFECTS OF KAOLIN CONTENT ON ELECTRO-OSMOSIS

by

MAJOR JAMES A. HARPER
United States Marine Corps

A Thesis Submitted to the Faculty

of the Department of Civil Engineering

in Partial Fulfillment of the

Requirements for the Degree of

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FOREWORD

The author wishes to express his appreciation to Professor E. J. Kilcawley for the freedom of action granted, and for his overall guidance during the course of this investigation. Special appreciation is also expressed to Professor S. V. Best for his encouragement, advice, assistance, and sympathetic understanding extended to the author throughout the investigation.

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ABSTRACT

The purpose of this investigation was to determine the relative effects that different percentages of kaolin clay within a soil mixture might have on the factors involved in electro-osmosis.

In order to provide a better understanding of the investigation, introductory information regarding the need for research into the phenomenon of electro-osmosis is given, along with a brief review of some of the previous work in this field. Some basic concepts of the theory of electro-osmotic flow are presented, followed by an introduction to the basic concepts of the nature of clays.

The apparatus used in the tests is described, and the procedure for the series of tests is outlined. A detailed explanation of the method of preparing and using reversible silver silver-chloride electrodes is given.

A series of seven tests was conducted. Six of the tests involved the use of the silver silver-chloride electrodes with varying percentage mixtures of kaolin and sand. One test was conducted with nickel silver electrodes to obtain a comparison of the relative effects of different electrode materials on the factors involved in electro-osmosis.

During each test the sample was subjected to an externally applied load intensity of 1/4 T/ft^2. In six of the tests a potential difference of 2.7 volts between

electrodes was applied, with resulting potential gradients of 1.15 to 1.36. In one test the applied potential was 1.35 volts, and the potential gradient was .68. Readings of time, current flow, height of piezometric rise, and change of sample thickness were recorded throughout each test. The heights of piezometric rise were plotted against time, and used in determining electro-osmotic permeability relationships. Atterberg limits and hydraulic permeability were determined for each sample, both before and after electro-osmosis.

Most of the results of the tests are presented in tabular or graphical form, and various aspects of the results are discussed. Electro-osmotic flow occurred in all samples containing 20% or more of kaolin. Atterberg limits and hydraulic permeability decreased after electro-osmosis. Electro-osmotic permeability was found to be considerably greater that the natural permeability in all samples containing appreciable amounts of kaolin.

Silver-silver chloride electrodes were more effective in producing electro-osmotic flow than were nickel silver electrodes. The silver-silver chloride electrodes also effectively eliminated the problem of unreliable height of piezometric rise determinations associated with nickel silver and some other types of electrodes by eliminating the evolution of gas in the cathodic chamber of the electrosmometer.

PART I.

INTRODUCTION

Since the earliest prehistoric times man has constructed facilities which he considered necessary or desirable for his comfort, health, or safety. At first these facilities consisted primarily of simple and primitive personal shelters. As civilization advanced, and man gained more construction knowledge, his structures developed into more elaborate ones for the social, cultural, and economic welfare of the community or group as well as the individual.

That man has been able, even since the earliest days of recorded history, to build practically any structure if given sufficient support in materials, labor, and time, and a suitable site, is indicated by such truly great construction feats as the Pyramids of Egypt, the Temples of Babylon, and the Great Wall of China, as well as some of the more complex and awe-inspiring structures of today. However, whereas in ancient times structures could generally be placed at locations that were most satisfactory from a construction standpoint, today such freedom of choice of location is not normally the case, and choice of location is dictated by other considerations.

Every structure, whether large or small, must be founded on soil or rock. Since most structures rest on soil, the role of soil as a foundation material and as a con-

struction material is one of fundamental importance. Most construction materials have been developed to the point where they may be manufactured or controlled such that their physical properties are well known, and their action under load predictable. However, soil, the one material which is encountered in the construction of most structures, is a very complex material, and only within the last 30 or 40 years has our knowledge of the physical properties of real soil been accumulated (25) (26), and concerted effort made to develop to any appreciable degree the potentialities of soil mechanics. Even though many significant advances have been made in recent years in the study of soil behavior, and the information now available is a tremendous asset to the engineer in the design of foundations and earth structures, there are still many problem areas for which definite answers are not available.

One of the most perplexing and very often costly problems encountered in foundation and earth structure work is the unwatering of the construction site in order to stabilize the soil and to provide safe and dry working areas. A considerable number of diverse methods for accomplishing this result have been advanced, but the very existence of a number of different methods is further indication that the problem is a complex one. Caissons, cofferdams, and bulkheads are effective under some conditions, but are expensive,

and in many cases impractical. Such methods as well points, grouting, chemical stabilization, and vacuum pumping are effective under ideal conditions, but they are primarily limited to soils possessing a certain degree of natural permeability. In fine-grained soils of low permeability, such as saturated clays, they are generally non-effective. For this reason, there exists a requirement for a relatively simple and inexpensive method of unwatering construction sites in fine-grained silt and clay soils.

As previously indicated, soil mechanics is a relatively new science. It has been defined (25) as the scientific approach to understanding of soil action, or the science dealing with all phenomena which affect the action of soil as associated with engineering. Through this scientific approach, the search for a satisfactory method of removing water from construction sites in clay soils has led to renewed interest and investigation into the applicability of the long known, but little understood phenomenon of electro-osmosis. This phenomenon, in basic terms, is the movement of a liquid with respect to a solid produced by an externally applied electrical force. In a soil this consists of applying a direct current to electrodes placed in the soil. The water then moves from the anode to the cathode where it may be removed by pumping or by gravity.

Even though there have been a considerable number

of laboratory investigations and some field applications of electro-osmosis in the last 20-25 years, most of the investigations have been sporadic and unrelated, and most of the field applications have been under the direction of one man - - Dr. Leo Casagrande. Our knowledge of this phenomenon has increased considerably but a need for much more investigation is indicated before precise answers regarding its practical application to construction problems can be given.

With this need in mind, this investigation was undertaken in the hope of providing an increase, however small it may be, in the understanding of the phenomenon of electro-osmosis and its application. The investigation was intended to parallel somewhat an investigation by Wallace (28), but investigating the effect on a different clay, and using electrodes of a different material.

PART II.

HISTORICAL REVIEW

Basic knowledge of the existence of the phenomenon of electro-osmosis is accepted as having been known for more than a century. However, investigations regarding its application to engineering problems have been limited to comparatively recent years. Its first practical application to a construction project was less than 20 years ago by Casagrande (7), although a number of laboratory and field investigations had been made a few years before.

In more recent years a greater number of investigations as well as a few field applications have been made. Only a brief review of some of the findings and applications will be made here for general information. In a number of cases other persons than those cited have produced similar findings. If a more complete review of past work is desired, attention is invited to works by Casagrande (9, 10) and Preece(19), which should be readily available, and by Koonce (18). Casagrande's report gives a complete review of past and present work, with the author's comments on the individual papers reviewed, and is thus particularly useful.

The discovery of the phenomenon of electro-osmosis is generally credited to Reuse, who found in 1807 that water would flow through a porous diaphram, from the anode side to the cathode side, when an electric current was applied to

the system.

In 1861 Quincke formulated the hypothesis that an electrification exists at the contact surface of a solid and a liquid prior to the application of any external electrical potential (17). Then, depending on the relative sign of the original charge, either the solid particles or the liquid will migrate to the appropriate pole upon the application of an electrical potential. Helmholtz presented the first mathematical treatment of the double layer concept in 1879 (19). Although the concept of the structure has been modified, the modern mathematical concept is based on Helmholtz's assumptions, and provides what is generally accepted as the basis of electro-osmotic flow today.

Dr. Leo Casagrande has undoubtedly been the foremost contributer to modern progress in the field of electro-osmosis. He has done a considerable amount of research, and has successfully applied the phenomenon to a number of engineering projects. Based on the discovery that by using aluminum electrodes instead of other metals, clay soils are stabilized and hardened irreversibly, he applied for a patent in Germany in 1934 (9). Subsequently, he also obtained patents on the process in the United States and Switzerland.

In 1936 Endell and Hoffman studied (13) the hardening of clays by treatment with aluminum electrodes, based on Casagrande's method. Their findings indicated that Atterbergs

liquid limit and the friction angle (ϕ) are increased and that the moisture content is substantially reduced when a soil is treated by this method. They conclude that this first attempt to harden clay soils for engineering purposes "rests on a sound theoretical basis" and that "there are excellent prospects for a successful application of this method in all cases of foundation and mining engineering in which a horizon of soft clay is encountered."

On the basis of favorable model test results, Casagrande in 1937 conducted full scale field tests of his method (9). Wood piles were sheathed in 1 millimeter thick sheet aluminum over its embedded length. The soil at the site was a homogeneous clayey silt of high compressibility and moisture content. Bearing capacity of the piles before treatment was 7 to 9 tons per pile. Treatment resulted in an increase to an average maximum bearing capacity of about 40 tons per pile.

The first large scale practical application of electro-osmosis to an actual engineering project was made by Casagrande (5) in 1939. During excavation of a long railway cut at Salzgitter, Germany, serious flow slides were encountered which prevented deepening of the cut. After only one day of electro-osmotic treatment, excavation was able to proceed to completion with steep and stable side slopes.

A second large scale application of electro-

osmosis was made by Casagrande when unstable conditions were encountered during excavation for U-boat pens at Trondhjem, Norway (5). Electro-osmotic treatment permitted successful excavation, even with practically vertical slopes.

In 1947 Preece (19) produced an excellent paper summarizing the pertinent facts and theory of electro-osmosis, with particular attention to the Helmholtz theory and physicochemical reactivities. He gives a comparison of electro-osmotic rates of flow and hydraulic flow as a result of laboratory tests, but his findings of decreased liquid limit and plasticity index are at variance with the findings of Endell and Hoffman.

Winterkorn's paper (30) of 1947 reviews the Helmholtz theory for the electro-osmotic flow in rigid capillaries, and points out that for a saturated capillary system the electro-osmotic permeability is a function only of the porosity and the physicochemical inter-relationships between the solid surface and liquid. From experiments he also concludes that electro-osmotic permeability is not a constant, but varies with moisture content and applied potential.

In 1948 Bernatzik (2) stated that his experiments had shown that electro-osmosis does not produce stresses in the pore water or in the soil structure. Casagrande takes issue with this conclusion, and states that "it is evident from the research conducted by several workers in this

field that electro-osmosis causes tension in the pore water " (9).

Gouze, de Buryn, and Joustra (14) conducted experiments concerning natural and electro-osmotic permeability, on apparatus similar to that used in the current investigation. They also developed mathematical equations for electro-osmotic permeability and electro-osmotic head, or height of rise in a piezometer tube. Their experiments showed that although the height of rise theoretically becomes maximum at infinite time, it actually reached a maximum and then gradually decreased.

In 1953 Shukla (22) concluded from his investigations that electro-osmotic treatment decreased Adderberg limits and increased shear strength, permeability, and compressibility. He showed a marked decrease in liquid limit, but much smaller decrease in plastic limit.

Boyer, Hart, and Kondner (3) conclude from their studies that electro-osmosis in conjunction with sand drains in soft ground would produce advantages of reduced settlement time, permit increased drain spacing, and decrease danger of failure.

Wallace (28) in 1957 concluded that electro-osmotic treatment of an illite and sand combination, using nickel-silver electrodes, increases the Adderberg limits, reduces hydraulic permeability, and produces a condition of

electro-osmotic permeability which ranges from 20 to 320 times as great as the hydraulic permeability, and that the degree of electro-osmotic permeability decreases with decreasing illite content.

The above has been but a brief outline of some of the past work in this field. However, it provides an indication of some of the progress that has been made, as well as some of the various and sometimes conflicting results that have been obtained. It appears evident, that additional research in the field is required, not only to clear up some of the conflictions, but also to provide information in areas that have not previously been investigated.

PART III.

THEORY

A. Introduction

Just as there have been a number of differing results and conclusions obtained from studies of electro-osmosis, there have been a number of theories and concepts advanced to explain the occurrence of the phenomenon. However, Helmholtz formulated the still generally accepted theory (30), and it can probably best be explained through his hypothesis.

Since this paper is concerned primarily with permeability relationships and related factors, the theory of these relationships will be presented, and the modified Helmholtz equation of electro-osmotic flow discussed. Also, because the primary engineering interest in electro-osmosis is in regard to its possible application to problems involving clayey soils, and because clays are so complex, some information and basic concepts of the nature of clays will also be given.

Further information may be obtained from the work of Preece (19), which contains an excellent summary treatment of many of the basic concepts and factors regarding clays and electro-osmosis.

B. Basic Concepts of Electro-osmotic Phenomenon

Electro-osmosis is a phenomenon which occurs in a

solid-liquid mixture when the mixture is subjected to an externally applied potential, or electromotive force. Actually there are two phenomena which may be caused in a solid-liquid mixture by an applied potential. One phenomenon occurs when an electrical potential is applied to a predominantly liquid system in which are suspended solid particles of colloidal size. In this case the solid particles move within the liquid toward the electrical poles, and the phenomena is called electrophoresis. If, however, the system is predominantly solid particles, the liquid moves within the system toward one of the electrical poles, and the phenomena is electro-osmosis.

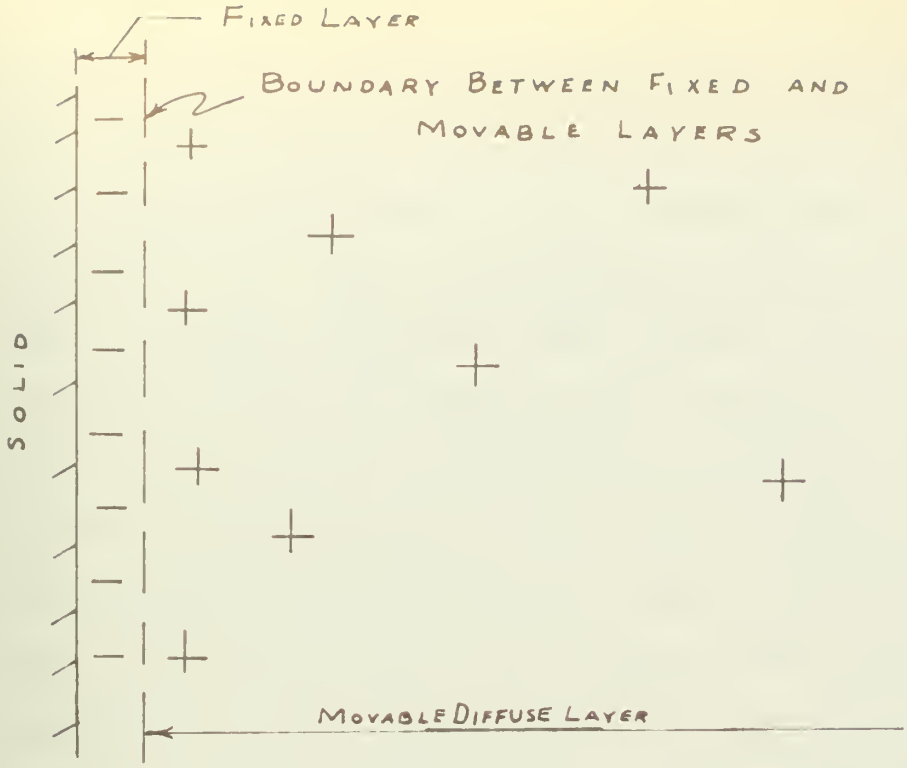
It is perhaps advisable at this time to point out that there is a distinct difference between osmosis and electro-osmosis. If two solutions of different concentration are separated by an appropriate semi-permeable membrane, the molecules of the solvent, but not those of the solute, will tend to pass through the membrane from the solution of lower concentration to the one of higher concentration (19). Since electro-osmosis primarily concerns the movement of the liquid solute, the distinction between the two phenomena is evident.

The systems in which electro-osmosis occurs may be single capillaries, bundles of capillaries, or porous materials (diaphrams) of natural or artificial origin, such as soils or porous ceramics (30). The liquid may be water,

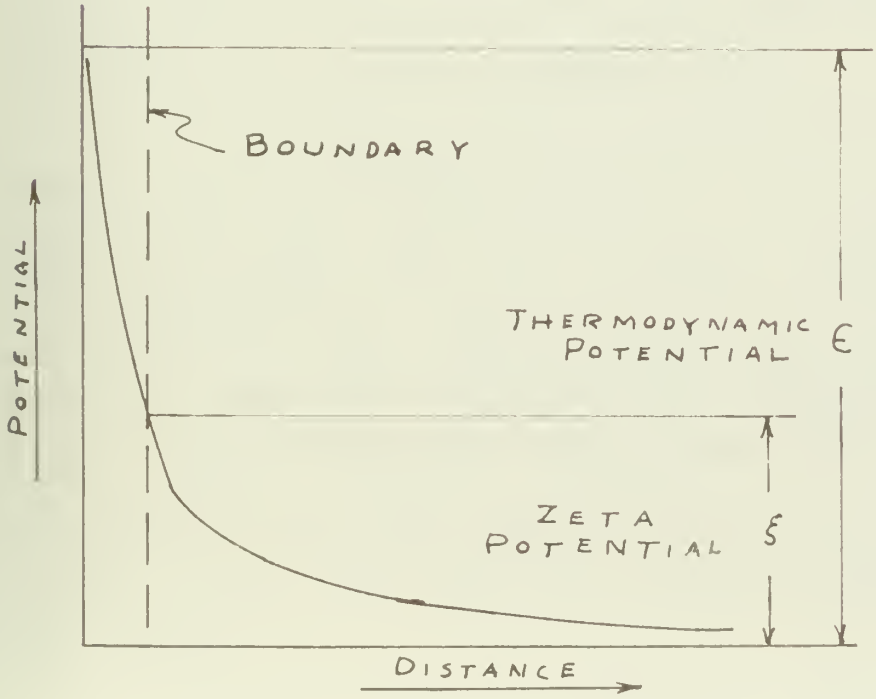
or any other liquid substance possessing low, or better, no, electric conductivity. Increases in conductivity of the liquid produce decreases in the efficiency of electro-osmotic liquid movement.

The theory of the existence of a double layer of electrically charged ions of the liquid existing at the solid-liquid interface enabled Helmholtz and subsequent investigators to explain the process of electro-osmosis. Adjacent to the solid surface there is pictured to be a fixed layer, formed by electrically charged ions of the liquid which are adsorbed, or attached, to the surface by the unsaturated charges or valences located in the surface of the solid. This is termed the fixed layer and is visualized as a thin rigid layer of ions of opposite charge to those of the solid, and with its thickness dependent upon the nature of the ions, the strength of the electro-static forces, and the amount of adsorbed water (19). This layer being fixed to the surface of the solid, any movement of the free liquid of the system must be against the surface of this fixed layer of liquid ions rather than against the surface of the solid. The other layer consists of a diffuse layer of ions of opposite charge to those of the fixed layer, and extends out into the liquid phase a varying distance. See Figure I.

Helmholtz visualized the double layer as essentially similar to that of a condenser, the two layers



DOUBLE LAYER
FIGURE I



ZETA POTENTIAL
FIGURE II

being separated by very small distances, and representing the parallel plates of the condenser. By applying condenser principles, he was able to solve mathematically for the zeta potential ( ). The zeta potential is that portion of the total potential difference which exists between the boundary separating the layers and the outer limit of the diffuse layer. The total, or thermodynamic potential difference is that which exists between the bulk of the solid and a distance somewhat beyond the outer limit of the diffuse layer (19). The quantitative relationship between total and zeta potential is shown diagrammatically in Figure II. The total potential depends upon the character of the solid and the solution with which it is in contact, and the zeta potential depends quantitatively upon the total potential, and the thickness of the fixed and diffuse layers.

Any increase in the concentration of ions in the diffuse layer will cause a decrease in the effective thickness of the double layer and a resulting decrease in the zeta potential (19). If the concentration is made sufficiently large, the sign of the zeta potential may become zero or even be reversed. The magnitude and sign of the zeta potential will then depend upon the nature of the several factors which enter into the development of the double layer.

When an external potential is applied across a solid liquid interface, the movable diffuse layer of the

double layer is displaced tangentially along the fixed layer toward one of the poles, depending upon the sign of the charge of the diffuse layer. If the movement takes place in a capillary tube, the free water in the tube beyond the diffuse layer will be dragged along with the diffuse layer, and a small thread of water will be discharged at the end of the capillary (19). This is the theory of electro-osmosis in its simplest terms. Since anything which tends to decrease the thickness of the double layer will also reduce the zeta potential, it becomes evident that the rate of discharge due to a given external electromotive force will depend upon the magnitude of the zeta potential.

The quantity of liquid moved through a single capillary in unit time under a given potential difference can be derived from the modified Helmholtz equation (6):

$$(1) \quad q_e = \frac{EDr^2\zeta}{4\mu L}$$

where

q_e = quantity of electro-osmotic flow
E = the applied electric potential
D = the dielectric constant of the liquid
r = the radius of the capillary
ζ = the zeta potential
μ = the viscosity of the liquid
L = the length of the capillary between electrodes

and all dimensions are in cgs and electrostatic units. A detailed development of this equation is given by Vey (27).

From this modified Helmholtz equation, Casagrande

(7) developed an equation for electro-osmotic flow which is similar to Darcy's law governing laminar hydraulic flow. If in the above Helmholtz equation we let $\frac{E}{L} = i_e$, the potential gradient, $\frac{D\zeta}{4\pi\mu} = C_1$, a constant (since most soils have a relatively constant zeta potential (7)), and $r^2\pi = a$, the cross-sectional area of the capillary, we then obtain for rate and velocity V of flow:

$$(2) \quad \begin{aligned} q_e &= C_1 i_e a \\ V_e &= C_1 i_e \end{aligned} \quad \text{for electro-osmotic flow}$$

compared to

$$(3) \quad \begin{aligned} q_h &= C_2 i_h a^2 \\ V_h &= C_2 i_h a \end{aligned} \quad \text{for hydraulic laminar flow}$$

A diagrammatical comparison of electro-osmotic flow with hydraulic flow in a single capillary is shown in Figure III. If applied to a bundle of N straight capillaries of total cross-sectional area A, with void ratio e, the corresponding total rates of hydraulic and electro-osmotic flow are respectively:

$$(4) \quad Q_h = Nq_h = (a \frac{e}{1+e} C_2)\, i_h A = k_h\, i_h A$$

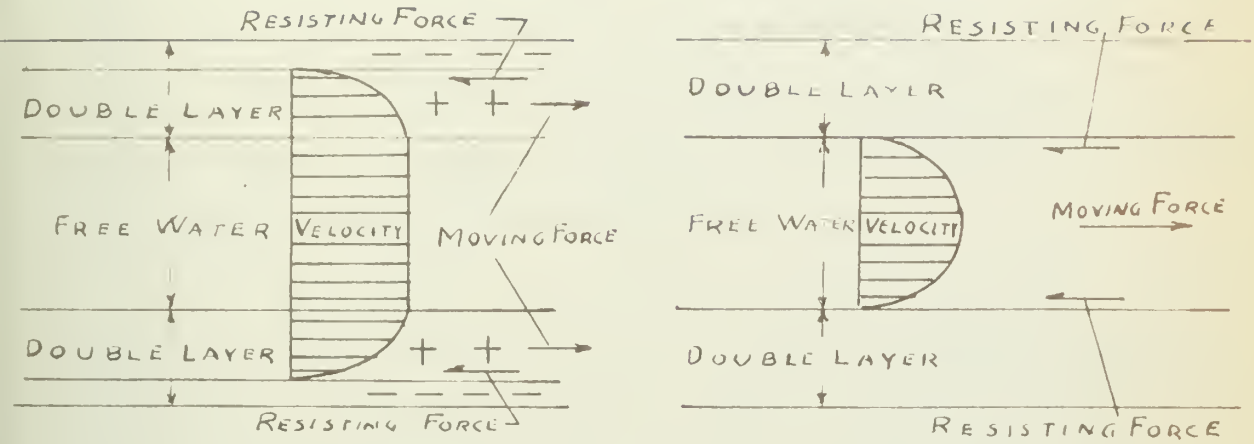
and

$$(5) \quad Q_e = Nq_e = (\frac{e}{1+e} C_1)\, i_e A = k_e\, i_e A$$

where k_h = the hydraulic coefficient of permeability

and k_e = the electro-osmotic coefficient of permeability

An important difference between hydraulic and electro-osmotic flow is emphasized by equations (4) and (5).



(a) ELECTRO-OSMOTIC FLOW (b) HYDRAULIC FLOW

COMPARISON OF ELECTRO-OSMOTIC FLOW WITH HYDRAULIC FLOW IN A SINGLE CAPILLARY

FIGURE III

Whereas k_h and the rate of hydraulic flow are proportional to the first power of the cross-sectional area of the individual capillaries, k_e and the rate of electro-osmotic flow are independent of the size of the capillaries. This is an important difference, and indicates that for a given zeta potential, k_e should be the same for sands, silts, or clays. Since hydraulic flow drainage is ineffective in clays because of small pore size, the possibilities of utilizing electro-osmosis become apparent.

Of course, it is recognized that the above equations and flow conditions are based on highly idealized conditions which do not actually exist in clays. Clays are highly complex, as will be pointed out later, the pores are not straight capillaries, nor are they uniform throughout a given mass, and the void ratio does not remain constant during electro-osmosis. However, this does not detract from the usefulness of the theory for visualizing what actually occurs.

Gouze, de Bruyn, and Joustra (14) investigated electro-osmotic flow conditions through the use of an electrosmometer similar to the one used in the current investigation. From the fact that application of an electromotive force causes water to rise in a piezometer tube located just back of the cathode in the electrosmometer, they developed a differential equation based on electro-osmotic flow in one direction opposed by hydraulic flow in the opposite direction.

By differentiating, they obtained:

$$(6) \quad k_e = \frac{k\,h}{U} \frac{e^{\frac{kOt}{F\,d}}}{\left(e^{\frac{kOt}{F\,d}} - 1\right)}$$

or

$$(7) \quad h = \frac{k_e\,U}{k} \left(\frac{e^{\frac{kOt}{F\,d}} - 1}{e^{\frac{kOt}{F\,d}}}\right)$$

where

h = height of rise above the constant level at time t after the start of the test
F = cross-sectional area of the piezometer tube
O = cross-sectional area of sample
k_e = electro-osmotic coefficient of permeability
k = hydraulic coefficient of permeability
U = electrical potential between electrodes in volts
d = distance between electrodes
e = the Napierian or natural logarithm base

The maximum height of rise theoretically occurs at infinite time, or when t = in equation (7), and

$$(8) \quad h_{max.} = \frac{k_e\,U}{k}$$

However, the height is found in actual tests to reach a maximum, then decrease with continued application of external potential. There are different opinions as to why this decrease from maximum occurs, but Casagrande (9) attributes it to decreases in hydraulic gradient and void ratio as a result of consolidation due to electrical treatment.

Schaad (21) indicates that there are several remarkable influences affecting electro-osmosis which the Helmholtz equation neglects. He points out that these influences are less evident and less important in large scale and field experiments than laboratory tests, and that they have less effect near the beginning of the test. For this reason he indicates that the values found in the beginning of the test are more accurate. By differentiating equation (7) with respect to time, and introducing t = 0, he obtained an equation for the electro-osmotic coefficient of permeability k_e at the beginning of the test:

$$(9) \quad k_e = \frac{F}{OE} \tan \alpha$$

where

F = cross-sectional area of piezometer tube
O = cross-sectional area of the sample
E = potential gradient $\frac{U}{d}$
α = the angle between the tangent to the height of rise vs. time curve and the horizontal at zero time.

This value of k_e is independent of the hydraulic coefficient k. However, Butler (4) obtained values with equation (9) that were in exceptionally close agreement with those obtained from equation (6).

There are a number of other thoughts, ideas, and interpretations of theory of electro-osmosis. However, it is

believed that the material presented above, along with some basic information regarding clays in the following subsection, should provide a basis for a satisfactory understanding of the tests conducted during this investigation.

C. Some Basic Concepts of Clays

In order that a better understanding of the effects of electro-osmosis on a soil-water system may be gained, some fundamental concepts of the nature of clays, the active fraction of soil, should be understood.

Electro-osmosis is said to be fundamentally a phenomenon of colloid and capillary chemistry (27). That it can therefore be closely associated with clays is indicated by the definition of clays as "disperse systems of the colloidal products of weathering in which secondary mineral particles of smaller dimensions than 2 microns predominate" (1). It has further been proven that clays are constituted of distinctly crystalline minerals.

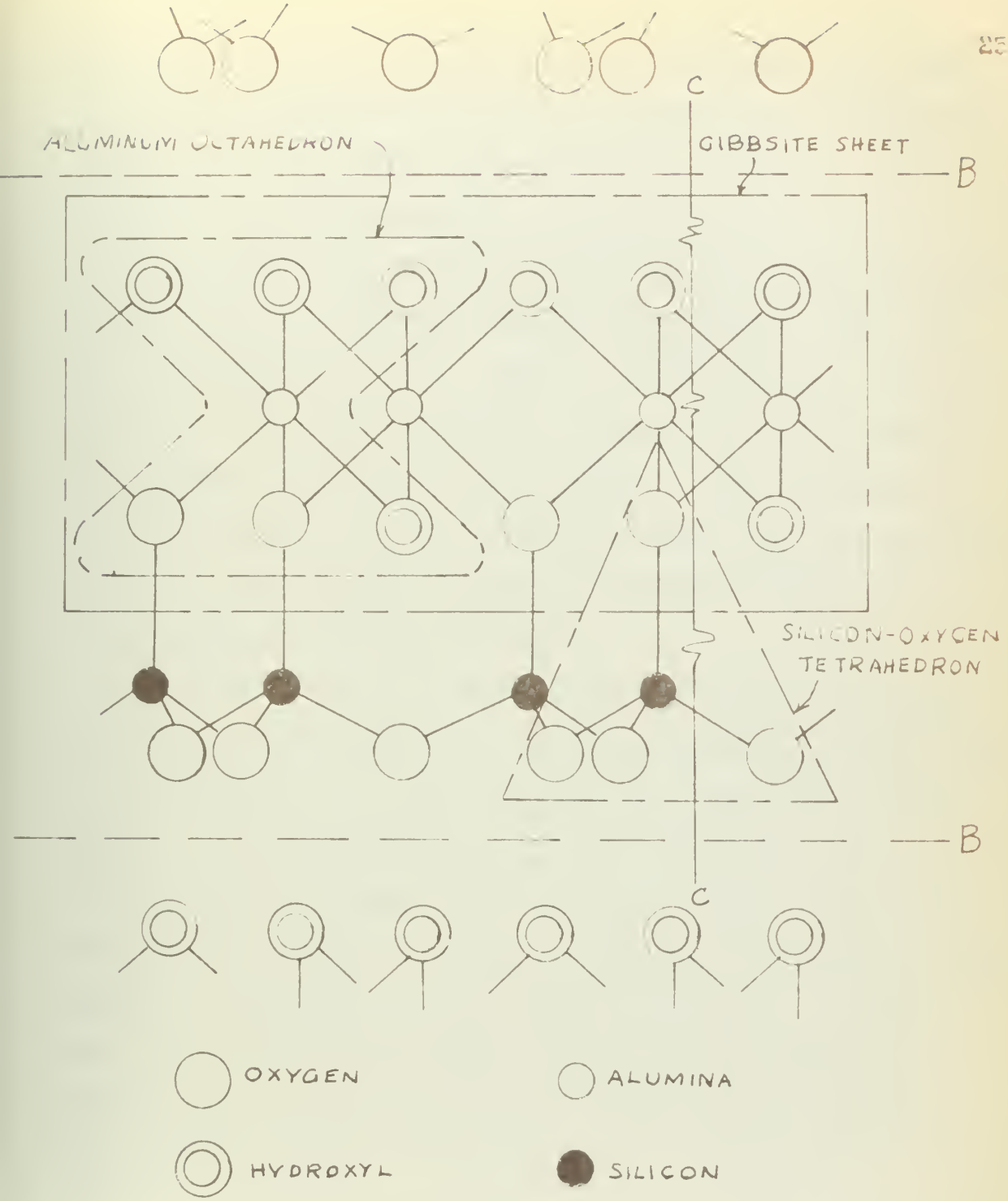
When ions or molecules combine to form a crystalline solid, they tend to group themselves in a geometrical arrangement that will result in the greatest possible degree of electrical neutralization. The most elementary grouping to form a crystalline structure is called a unit cell. For electrical neutralization within the structure, the internal electrostatic forces must be balanced. The source of the electrostatic charge can be considered an excess charge on an ion, and an unsatisfied valence on a molecule (19).

There are two basic types of unit cells which are the principal constituants of the clay minerals. These are the silicon-oxygen tetrahedron and the aluminum-hydroxyl

octahedron. Each of these unit cells is bonded by electrostatic forces to unit cells of the same type to form the elementary lattice structures called the tedrahedral silicon sheet and the gibbsite sheet, respectively.

Based upon the character of their space lattice, clay minerals are classified into three main groups, each of which takes its name from its principal member. These groups are Kaolinite, Illite, and Montmorollinite. The clay mineral of primary interest to this investigation being Kaolinite its space lattice is shown in Figure IV. The arrangement of sheets is such that they form a 1:1 lattice consisting of a single silicon-tedrahedron sheet and a single gibbsite sheet bonded tightly together by an equality of plus and minus valences. There is also a tight bonding between the adjacent lattices due to a strong affinity between the adjacent oxygen and hydroxyl layers at the interfaces, or basal cleavage planes B-B, between the lattices.

If the lattice were continued an infinite distance, it would be electrostatically neutral since there would be no unsatisfied valences. Also, since separations along the basal cleavage planes do not produce broken valence bonds, this form of separation does not tend to increase total surface attractive forces. However, these separations are always accompanied by breakages parallel to the C-C plane, which must sever valence bonds and therefore increase the number of unsatisfied valences (19). It follows then that



KAOLIN SPACE LATTICE
FIGURE IV

the smaller the clay particle size, the greater the number of surfaces, edges, and corners, and hence the greater the number of broken bonds and unsatisfied valences. This in turn means greater activity in the clay.

The clay tends to satisfy the electrical unbalance caused by the unsatisfied valences by adsorbing ions from the surrounding solution. This is possible since ions are atoms that have lost or gained neutrons, and thus have a net negative or a net positive charge. The clay preferentially adsorbs a layer of negative ions, which themselves attract a counter layer of positive ions to produce the double layer previously described.

The thickness of the double layer and the force with which it is held to the solid are dependent on the size of the adsorbed ions, and the degree to which they are hydrated. If the original solution is replaced by one containing different ions, or if entirely different ions are added to the solution, this may result in a decrease in the degree of hydration, or in a lower net charge. In this case the new ions may replace the ions of the original double layer either in part or entirely. This is called base exchange (19).

As has previously been discussed, the quantity of electro-osmotic flow depends upon the zeta potential, which in turn depends on the thickness of the adsorbed layer, and the thickness of the diffuse layer. In view of this, and

the clay factors outlined above, it is readily apparent that clay soils should be readily adaptable to electro-osmotic flow.

PART IV.

MATERIALS AND APPARATUS

A. Introduction

In order that the effect of kaolin content on electro-osmosis, and the permeability relationships involved might be investigated, it was necessary that an electrosmometer be available. Fortunately, an adequate electrosmometer was available among the equipment of the Civil Engineering Department of the institute. It had been constructed and used by Butler (4) and Tarran (24), and later used by Wallace (28). Its design is excellent for the purposes of the current investigation in that it can also be used as a falling head permeameter by merely raising the level of water to the desired height in the piezometer tube and letting it flow back through the sample and out the overflow tube on the opposite side. This permits the natural permeability to be determined both before and after the electrical treatment of the sample, without the necessity of preparing a separate sample just for permeability determinations. Some modifications in the apparatus were found to be necessary or desirable, and were made. Further details concerning these modifications will be given later.

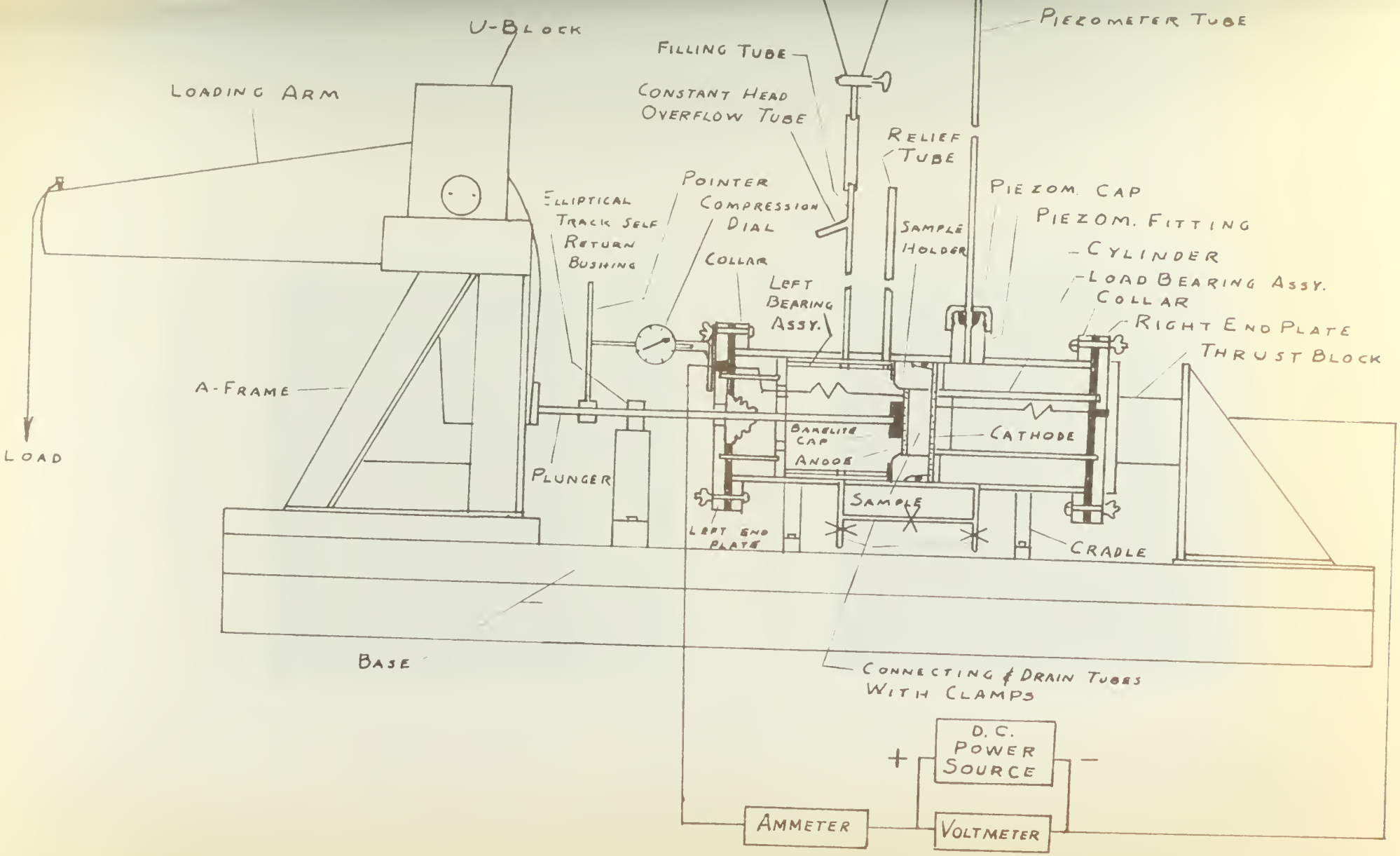
Also available within the Civil Engineering Department was a variable direct current power source. This equipment was made available for the investigation, and permitted

the electrical gradient to be maintained at a desirable figure. Current flowing during electrical treatment was measured on a three-range D.C. milli-ammeter, and voltage was measured on a single range D.C. voltmeter, both of which were obtained on loan from the Electrical Engineering Department.

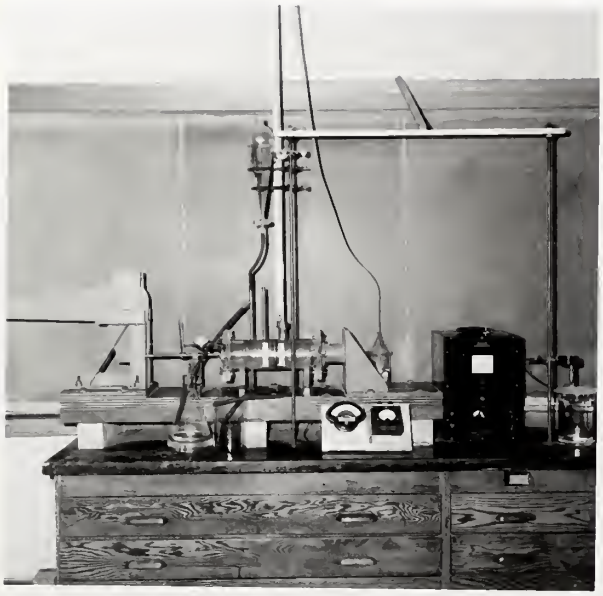
B. The Electrosmometer

Only a general description of the electrosmometer considered adequate for a satisfactory understanding of its operation, along with modifications made, will be given here. This, along with a schematic illustration and several pictures, should provide ample basis for a satisfactory understanding of the apparatus and its components. A complete discussion of the design and construction of the electrosmometer is given by the designers, Butler (4) and Tarran (24). A schematic diagram of the electrosmometer and electrical equipment is given in Figure V. The apparatus is shown in use during a test in Figures VI and VII.

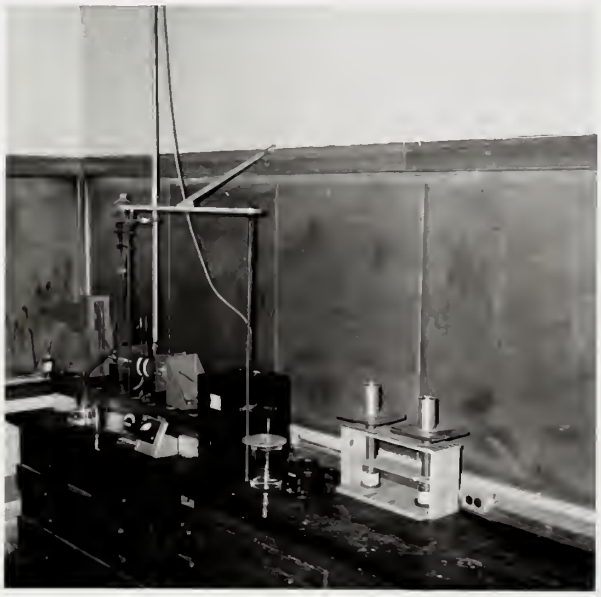
The cylinder, or main body, of the electrosmometer is made from a 4" inside diameter lucite tube 13" long. A 7" x 7" x ½" lucite collar with cutout to size of the outside diameter of the tube is cemented over each end of the cylinder. Each collar is drilled with 8 bolt holes to match holes in the two 7" square end plates, which are bolted to the collars along with rubber gaskets for water tightness.



Schematic Diagram of Electrosmometer
Figure V



Front View of Electrosmometer
and Electrical Equipment
Figure VI.



Oblique View of Electrosmometer
and Related Equipment
Figure VII.

A 1-1/8" thick sample holder with 2.505" diameter sample compartment, fits inside the central portion of the cylinder. The outside perimeter surface has a .7" tapered section so that a 4" O.D. rubber "O" ring can fit around the sample holder and against the inside wall of the cylinder to seal off flow of water between adjacent sections of the cylinder except through the sample.

Loads of various intensities can be applied to the sample by suspending weights from the loading arm. The load is transmitted to the sample through a stainless steel plunger which bears against the anode, which in turn is in contact with the sample, and free to move longitudinally within the sample holder. The plunger enters the cylinder along its axis through a hole in the center of the end plate. Leakage is prevented by an accordian type rubber nipple which is cemented to the end plate and the plunger. The load is transmitted through the sample to the cathode, which is backed up by the load bearing assembly. The load bearing assembly bears against the right end plate, which is backed up by the thrust block. Since the thrust block is bolted to the base, there can be no movement under the load except for expansion or contraction of the sample. An eliptical track, self return bushing is located between the loading assembly and the cylinder to guide the plunger and to take any vertical components of thrust from it.

A removable brass pointer is mounted on the

1. Left end plate with plunger, anode, and lead-in wire
2. Brass pointer and deflection gauge
3. Left bearing assembly
4. Spacer gasket used between left bearing assembly and sample holder
5. Sample holder
6. Cylinder or main body
7. Rubber "O" ring
8. Load bearing assembly
9. Right end plate, cathode, and lead wire

Parts and Accessories of the Main Body
of the Electrosmometer
Figure VIII.

plunger between the loading assembly and the bushing, and makes contact with a deflection gauge mounted on the collar of the cylinder. This permits determination of consolidation, expansion or other movement of the sample.

A filling tube and relief tube of rigid vinyl plastic are bonded into the top of the cylinder on the anode side. A threaded plastic fitting is installed in the top of the cylinder on the cathode side so that the piezometer may be attached or removed when required. The piezometer used was a glass tube with a cross-section of .4395cm^2. A small tube at the bottom connects the anode and cathode sides of the cylinder and permit uniform filling and draining.

The wires carrying the current through the osmometer pass through the end plates, to which they are permanently sealed. The lead-in wires are connected to the electrode wires through a plug and jack connection. The lead wires are each soldered to a banana jack. A banana plug connects to each electrode wire by means of a set screw. The plug fits into the jack to form a satisfactory connection and permit disconnection and removal of the electrodes when required between tests. The exposed metal surfaces were coated with vaseline to prevent current leakage, electrolytic action on the metal, and rust in the water. Figure VIII shows parts and accessories of the main body of the electrosmometer,

A glass reservoir with stopcock was installed

above the cylinder to provide a sufficient water supply to the filling tube in order that a constant head might be maintained. The stopcock permits drip flow in order to eliminate frequent filling.

The base for the assembly consists of a double thickness of 3/4" plywood mounted on two 2" x 2" x 3/16" x 4' 6" angles running the length of the base. The cylinder rests on 2 wooden cradles, and the eleptical track self-return bushing is mounted on an oak block bolted to the base. The loading arm assembly and thrust block are bolted to wooden platforms bonded to the base.

In order to permit easy determination of sample thickness, a simple calibration of the compression dial was required. The apparatus was assembled as for a test, except that 2 filter papers and a carbon disc, all of known thickness, were placed in the sample holder instead of a sample. With the test load of 1/4 T/ft^2 applied the brass pointer was tightened at a marked point on the plunger, and the compression dial read. The pointer was always placed at the same locations for each test. With the dial reading and thickness of the electrodes at the time of calibration known, it was an easy matter to determine the sample thickness for any test by algebraically adding the difference in these figures at a given time.

Certain changes in the apparatus were found to be necessary to permit satisfactory or easier operation. The

base was raised 4" above its supporting platform by inserting 4" x 4" x 13" wooden blocks under the ends and center of the base. Prior to raising it was exceedingly difficult to reach under the base and tighten the bolts to the thrust block and self-return bushing through the 2" space allowed by the previously installed 2" x 4" blocks. Also, a 2-position bracket to hold the compression dial gauge was fabricated to prevent the gauge from slipping or dropping against the plunger arm.

It was found that the slight flow of water from the reservoir permitted by the dripping through the stopcock tended to adhere to the sides of the filling tube, and would generally go out the top of the overflow tube before reaching the constant level. A thin 1/8" x 4" aluminum tube was split at the end and inserted in the top end of the rigid portion of the filling tube, such that it extended below the constant head level. This eliminated the problem.

Heights of rise in the piezometer tube that were considerably greater than any previously encountered made two modifications necessary. The piezometer was extended to a height over two hundred and thirty-one centimeters above constant level. This was within 1 inch of the room ceiling. The high pressure head caused the sample holder to move laterally along the inside of the cylinder, from the cathode toward the anode side, causing the sample to be pushed out of the holder by the plunger as the holder moved.

This movement was possible because the sample holder was held in place within the cylinder only by the frictional resistance of the 4" rubber "O" ring which has been positioned between the sample holder and the cylinder wall by force. The original design provided positive sample holder position and stability control in the direction of the cathode only. This was provided by the load bearing assembly. To eliminate the movement, a left bearing assembly was fabricated. It consists of a length of 4" O.D. lucite tube that just fits inside the cylinder, and extends from the sample holder, from which it is separated by a flat rubber gasket with 3" center opening, to the plunger support attached to the left end plate. Holes 1/2" in diameter were drilled in the top and bottom in locations opposite the filling, relief, and drain tubes to prevent blocking these entrances into the cylinder.

The connecting tube under the cylinder was a single piece of continuous tube with clamp, but with no opening to the outside to permit drainage. The tube was cut and 2 T's and additional clamps installed to permit separate sampling and draining of water from the anode and cathodes sides of the cylinder without inter-mixing.

Prior to the test period it was noted that, because of high heat and low humidity from steam radiators in the room, considerable evaporation from the piezometer tube was occurring. This amounted to a loss of almost 1 cm. of height of water in the piezometer tube in one 24-hour period.

An anti-evaporation device was devised, and after it was installed no further evaporation was noted. This consisted of a 4" glass funnel inverted over a 1-liter beaker and connected to the top of the piezometer tube by means of a 1/4" flexible rubber hose. The beaker was filled with water and the circle of contact between the funnel and beaker was sealed with cellophane tape, leaving only a small opening through the pouring spout of the beaker. Thus, any tendency toward evaporation in the piezometer was counter-acted by the atmospheric pressure of evaporation in the beaker.

C. Electrical Components and Equipment

1. Electrodes. Previous users of the equipment (4, 24, 28) reported encountering difficulties in obtaining reliable piezometer rise readings due to excessive bubbles forming within the cylinder as a result of evolution of gas at the cathode. Electrodes in those instances consisted of porous nickel-silver discs approximately 1/8" thick.

It was noted from the paper by Rollins (20), that the difficulties associated with gas formation had been eliminated through the use of reversible silver silver-chloride electrodes. It was then decided that an attempt should be made to produce and utilize electrodes of this type for the current investigation.

The diameters of the electrodes were determined by the design of the electrosmometer and are required to be

2.5" and 4.0" for the anode and cathode, respectively. The material selected for the electrodes was silver, fine grade, cut into circular discs from 1/32" flat sheets. These were then perforated by drilling 1 mm holes with a standard No. 60 drill, to a density of 64 holes/in.^{2}, uniformly spaced. The entire anode, except for a small area for attaching the wire, was perforated. However, only an equivalent 2.5" diameter circular area in the center of the cathode was perforated, since that is the only area of actual contact with the sample.

The electrode wires were B&S standard 20 gauge fine silver, and were attached to the electrodes by means of silver solder. Since difficulties were encountered in initial attempts to attach the wires, this service was performed by a local jeweler.

Prior to use in the tests the silver was chloridized, in a manner to be described under Procedure, to obtain electrodes of silver silver-chloride. These electrodes were then used on all except one test. In the case of the exception, the previously mentioned nickel-silver electrodes were used in an attempt to obtain an additional comparison of the results of these tests with those obtained by Wallace (28).

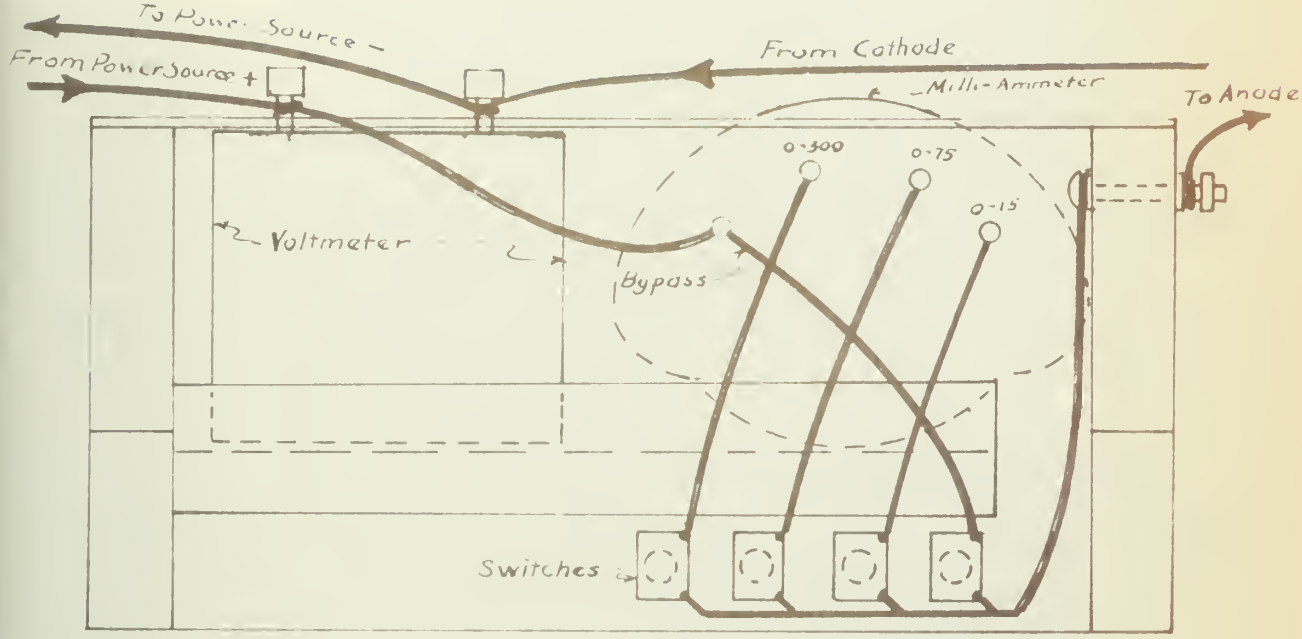
2. Power Unit. A portable D.C. power unit belonging to the Civil Engineering Department was made available for the investigation. The unit is a Fisher Powerhouse

No. 9-518 manufactured by the Fisher Scientific Company. When the unit is attached to a standard 115-volt 60-cycle line, it becomes a source of continuously variable direct or alternating current. A built-in dry disc rectifier and filter is used as the direct current source. The D.C. voltage varies from 0-10 volts and is controlled by a large dial on the front of the unit. It has a maximum current rating of 10 amperes, but the current for these tests was measured in milli-amperes. The unit has less than 5% ripple at maximum current output, but there are slight variations in the voltage output which are caused by variations in the A.C. supply. Since the voltage variation does not exceed .05 volt, it is of no importance in the effect it has on electro-osmosis.

3. Metering Control Unit. Although there is a voltmeter and an ammeter on the power unit, they could not be read with suitable accuracy in the ranges used during the tests. Therefore separate meters, provided by the Electrical Engineering Department, were used. The voltmeter was a Weston Model 301, single range, 0-5 volts, D.C. The 0.1 volt divisions gave satisfactory reading accuracy. The ammeter was a Weston Mil-Ammeter, Model 269, No. 15184, with ranges of 0-15, 0-75, and 0-300 milli-amperes. The two lower ranges were used during the electro-osmosis tests, and the upper range during the process of chloridizing the electrodes.

To eliminate the necessity of changing wires each time a change in ammeter range was required, and to provide a compact control unit, a metering and switching control panel was constructed. This consisted of mounting the voltmeter, ammeter, and toggle switches, along with necessary wire connections on a board on an inclined base. Figure IX shows the metering control board, and indicates the wiring diagram used for the tests, as well as for chloridizing the electrodes.

Except for the short lengths of silver wire between the electrodes and the banana plugs, and single strand fabric covered wires from the metering control board to the electrodes during chloridizing, all wires used for electrical connections were a standard 6-conductor, rubber insulated type. Yoke-type fittings were crimped to the ends of the wires to provide for easy attachment to terminals.



REAR VIEW

SCHEMATIC DIAGRAM OF METERING UNIT
AND
WIRING DIAGRAM

FIGURE IX

PART V.

PROCEDURE

A. Chloridizing of the Electrodes

Prior to the tests the silver electrodes were chloridized by electrolysis in 0.1 N hydrochloric acid solution to provide reversible silver silver-chloride electrodes. This was done so that undesirable gas evolution at the cathode during the test might be eliminated. The method used was based on limited information of the procedure used by Goring and Mason (15).

The chloridizing process involves the breaking down of the electrolyte, hydrochloric acid, with the passage of chloride into solution as ions and the liberation of hydrogen to the air as a gas. At the same time there is a passage of silver from the anode into solution as ions. The chloride ions and silver ions then combine to form the insoluble silver chloride salt (16) as follows:

$$\begin{array}{rcl} Ag(s) & \rightleftharpoons & Ag + e \\ Ag + Cl & \rightleftharpoons & AgCl(s) \\ \hline Ag(s) + Cl & \rightleftharpoons & AgCl(s) + e \end{array}$$

The solid silver chloride forms on the silver electrode, thus producing a resulting electrode of silver base with a layer of silver chloride on the outside surfaces.

The electrolyte container used was a 2-liter beaker. The electrolyte was prepared by mixing 200 cc of 1.0 N HCL with 1800 cc of distilled water, thus forming two liters of

0.1 N solution. A lucite support frame was fabricated for each size electrode. The frame for the size electrode to be chloridized at a particular time was placed in the bottom of the beaker, with the notched support arms extending vertically up into the solution. The electrodes were placed in the notches of the support arms, where they were supported at three points around the circumference. In this manner, the electrodes were supported horizontally in the solution, and about 2 inches above the bottom of the beaker.

The cathode used during electrolysis was a platinum disc 1½" in diameter and .005 inches thick, and fused to a small platinum wire for connection into the electrical circuit. The platinum cathode was then suspended by its wire so that it was parallel to, and approximately 3/4" directly above, the silver electrode in the electrolyte. The cathode was held at a constant elevation above the silver electrode by inserting a conical lucite peg into the hole in the cover, thus binding the electrode wire to the cover. Both sizes of silver electrodes acted as anodes during the chloridizing process. However, only one was processed at a time.

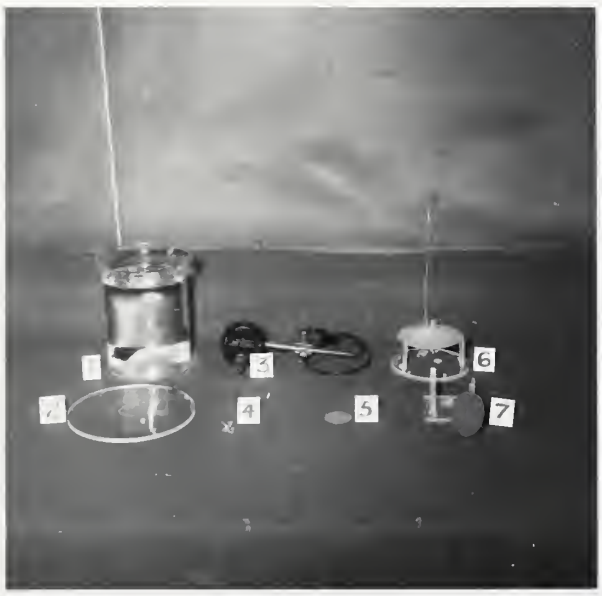
The electrolyte was covered to prevent dust and foreign objects from entering. This was accomplished by using a 7" circular lucite sheet 1/4" thick, which was drilled with two 7/64" holes for the electrode wires to pass through, and a 1/4" hole for the insertion of a stirring rod. The

electrolyte was continuously stirred mechanically by a glass rod with propeller shaped tip, attached to an electric variable speed stirrer supported above the beaker. Current to the stirring apparatus was provided from a 115 volt wall plug, through a "Variac" variable current control apparatus.

The silver electrode wire was attached by means of a spring clamp to a single conductor copper wire from the positive terminal of the metering control unit. The platinum cathode wire was attached in the same manner to the negative terminal of the voltmeter on the metering control unit. This is indicated schematically in Figure IX. Except for the power unit and metering control unit, the equipment for the chloridizing operation is shown in Figure X.

Before being placed in the electrolyte, the electrodes were thoroughly washed with distilled water, then cleansed by immersion in a dilute solution of nitric acid (1 part concentrated acid to 4 parts distilled water). An emersion time of approximately two minutes provided adequate cleansing without corrosion of the electrodes. After removal from the acid they were thoroughly washed in distilled water again. After they were thoroughly dried by being placed in an oven at 110° for a period of several hours, their weights and thicknesses were determined.

The electrode to be chloridized was then placed on its support frame and lowered into the electrolyte. The cover, with the stirring rod extending through, was placed



1. Two-liter beaker containing electrolyte
2. Beaker cover
3. Variable speed stirrer motor
4. Glass stirring rod with propeller shaped tip
5. Platinum cathode
6. Large silver electrode (before chloridizing) on support frame
7. Small electrode (previously chloridized) and support frame

Equipment for Chloridizing Electrodes
(Power source and metering equipment
not shown)
Figure X.

View of Electrode Chloridizing Equipment
During Chloridizing Operation

Figure XI.

over the beaker. The electrode wires were clamped to the wires of the electric circuit, and the stirring apparatus turned on. The current was then turned on, and the chloridizing began. The current flow was set at 190 milli-amperes for the 2.5" electrode, for a current density of 3 ma. per $cm.^2$ of electrode surface area. Since the maximum range of the milli-ammeter was 300 ma, the current for the 4" electrodes was set at this figure, with a resulting current density of approximately 1.8 ma. per cm^2.

As soon as the current was turned on, small hydrogen bubbles were noted forming and flowing off from the platinum cathode. They continued to be given off in a steady stream all around the cathode and its attached wire when the current was on throughout the chloridizing process. Also within a few moments after the current was turned on, the silver anode began to show a slight change in color, to a greyish brown. The change in color was caused by the formation of the layer of silver chloride over the silver. As the layer became thicker, the color became a shade of blue-grey.

As the chloridizing progressed, there was a steady decrease in current flow, until after one hour the flow indicated on the milli-ammeter was approximately half the initial flow. At the one hour point the current was cut off, then the flow was reversed by switching the wires on the terminals at the power unit. This was done to provide a porous layer of silver chloride. The current was allowed to

flow in the reverse direction for approximately 15 seconds, by which time the slight deposition that had appeared on the cathode toward the end of the previous one hour period was removed. Also at about this time a slight discharge of hydrogen gas from the anode was noted. The current was then turned off, and the wires again switched to their original terminals. The process was repeated until a suitable thickness of silver chloride had been formed on the anode, with the current being reversed every hour.

When the current was again turned on in the original direction, the current flow instantaneously exceeded the maximum range of the milli-ammeter scale. For this reason, and to prevent possible damage to the meter, the current flow was directed through the by-pass line around the meter for about the first half minute. The current flow then decreased rapidly down to a value near what it had been before the reversal of flow. The flow was then increased by turning the knob on the power unit until the milliammeter indicated the original starting value of 190 ma. or 300 ma., depending on whether the 2.5" or 4" electrode was being treated.

Whereas the current drop during the first hour of chloridizing was approximately 50%, there was less drop for each succeeding hour. The drop amounted to only about 10% after 4 or 5 hours for the 2.5" electrode, and after 6 or 7 hours for the 4" electrode. After these times, it was

considered that a satisfactory thickness of silver chloride had been formed, so the current was turned off without reversing the flow after the final hour of anodizing of the silver electrode.

After being removed from the electrolyte, the electrodes were again washed by allowing distilled water to flow over them to remove the acid, but without rubbing or otherwise handling the treated surfaces. They were then dried, and again weighed and calipered for thickness. They were then ready for use in the electrosmometer during the electro-osmosis test of the soil sample. However, until the time for the electrodes to be actually inserted into the osmometer, they were stored in a protected location in a cabinet where they would not be exposed to the light rays from the sun or fluorescent lights, since these light rays have a deteriorating effect on the silver chloride.

After a test in the electrosmometer, the silver chloride layer on the cathode was thinner and less tightly bonded to the silver, and it tended to flake off in sheets in the areas where the bond was loose. For this reason, the remaining silver chloride was removed from the cathode after each use in the osmometer. The removal was accomplished by immersing the electrode in concentrated ammonium hydroxide until the remaining silver chloride was sufficiently loosened to where it could be scaled off. The cathode was then ready to be rechloridized for further use in the same manner as before.

The anode normally appeared to have a tightly bonded and more stable layer of silver chloride after use in a test. For this reason, the layer was removed only if it appeared to have weak spots. Then, after being cleansed in distilled water only (no nitric acid), the anode was rechloridized by adding to the layer remaining on the electrode.

B. Sample Characteristics

The soil samples used in the tests of this investigation were composed of mixtures of kaolin and fine grained sand passing a No. 40 sieve. The general chemical composition of kaolin is:

$$Al_4Si_4O_{10}(OH)_8.$$

The particular kaolin used was obtained from Wards Natural Science Establishment, Inc., Rochester, New York, and occurs in a clay pit in Dry Branch, Georgia, Dana 492. This clay was determined by Dearth and Williams (12), through x-ray analysis, to be 90% pure kaolin.

The Atterberg limits of the kaolin were determined to be: Liquid limit 43.7, plastic limit 27.7, and plasticity index 16.0. The specific gravity is 2.598. The clay as received was in solid lumps, varying in size up to about three inches. For this reason, it was necessary to grind it to powdered form in a mechanical grinder.

The sand used was Cow Bay Sand, so named because it came from Cow Bay, Long Island, N. Y. It was in stock at

the institute, having previously been obtained from a local building supply company. It was prepared for use by sieving out the coarse particles, and retaining only those passing the No. 40 sieve. The minus 40 size particles used were approximately 90% angular quartz, about 9% rock fragments believed to be of ferro-magnesium composition, and small amounts of white mica and schist.

The specific gravity of the sand was determined to be 2.72. As received, it had been previously washed, and was considered to be sufficiently clean to use without further washing.

The Atterberg limits for each sample were obtained, as nearly as possible in accordance with A.S.T.M. Standards 423-54T and 424-54T, prior to testing, and at the conclusion of the test. The void ratio was obtained at the start of each test, and the natural permeability was determined within the electrosmometer prior to, and at the conclusion of electrical testing.

C. Sample Preparation

In order that the only appreciable difference in the samples for the different tests should be the varying kaolin-sand percentage relationship, it was considered necessary that all samples be prepared under as nearly identical conditions as possible.

It was also considered appropriate to have the

sample under some load, and that the load for each sample should be the same. A load of 1/4 ton per ft.^{2} was considered to be satisfactory, and consistent with the loading used by Wallace (28) in his investigation with illite. Sufficient weight was suspended from the loading arm to provide this load on the sample. In order to prevent appreciable consolidation of the sample from occurring during the test, the samples were prepared several days prior to the testing date, and were preloaded with sufficient weights to apply 1/4 T per ft.^{2}.

Representative samples of kaolin and sand were measured for each test. They were mixed by dry weight to give the desired percentage of each in the mixture. It was found that a total weight of 400 gm. gave about the most satisfactory volume of sample, and made the determination of the weight of each material to provide the proper percentage mixture a simple matter. The kaolin were added in small increments in a large porcelain dish, and thoroughly dry mixed. Then sufficient distilled water was added to bring the mixture to approximately the liquid limit. It was mixed by hand with a spatula until it appeared wet throughout, after which it was thoroughly mixed by using a household type food mixer.

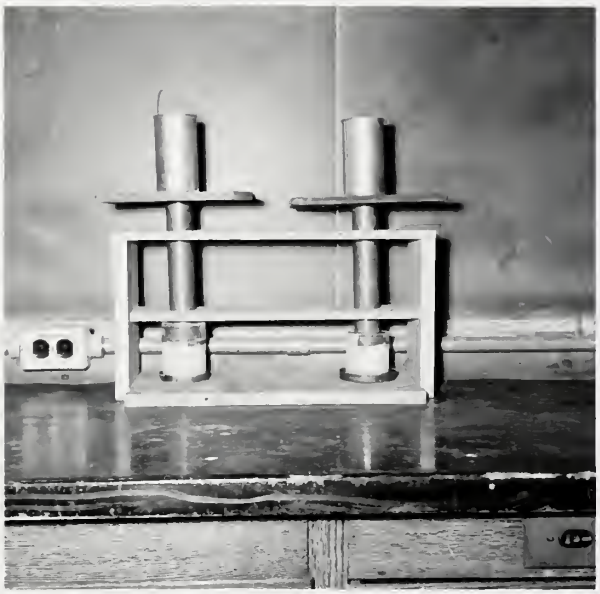
The sample was then prepared for preloading. This was accomplished by placing the soil into 2½" I.D. lucite tube approximately 4" long. The soil was placed in thin lifts

on top of a carbon disc and filter paper which had previously been placed in the bottom of the upright tube. The tube was placed vertically in a 3½" soil sample tube lid, and after each lift of sample was placed into the tube, the lid and tube were picked up together and tapped gently on a rubber pad. This assisted in distributing the sample evenly in the tube, and expelled any entrapped air bubbles from the mixture. After a sample height of about 2½" had been attained, another filter paper and carbon disc were placed on top of the sample. The sample was then placed under load in the preloading frame for a period of about 4 to 6 days. The top and bottom porous carbon discs were supplied with water and kept wet to prevent drying of the sample. Figure XII shows samples under load in the preloading frame. This procedure resulted in samples that were relatively uniform and free of air voids.

The remainder of the mixed sample was placed in an air tight jar and allowed to set for a minimum of 24 hours to provide a more uniform distribution of moisture in the sample, and a more complete hydration of the clay. This portion of the sample was then used to obtain Atterberg limits.

D. Assembly of Apparatus and Sample

After the sample had been preloaded for a suitable period of time, the load was removed, and the sample was ready to be inserted into the sample holder for the test.



Preloaded Samples in Loading Frame

Figure XII.

Just prior to removing the load from the sample, the sample holder, a carbon disc, two filter papers, and two 3" diameter thin flat glass plates were weighed. One plate was placed on the work table, with a filter paper, the carbon disc, and the sample holder, with anode side down, placed on top such that the carbon disc lay within the lower portion of the sample cavity.

The soil was pushed through the preconsolidation tube until the porous disc and filter paper that were under the sample during preloading were just beyond the end of the tube. The disc and filter were carefully removed in order to prevent damage to the bottom of the sample. The tube was then centered over the sample holder, and the sample was pushed directly into the sample holder. This was accomplished by applying pressure to the top porous disc with a piece of 1½" copper tubing. The sample was then cut off flush with the cathode side of the sample holder by using a wire type cutter. The other filter paper and glass plate were immediately placed over the exposed end of the sample to prevent loss of moisture until the sample could be weighed.

A small quantity of the unused portion of the sample mixture was then immediately placed in a weighing container for initial moisture content determination. The test sample, along with the glass plates, filter papers and carbon disc, was then weighed, after which the moisture content sample was weighed. In this way the weight and moisture

content of the sample were obtained so that they might be used with the sample volume in determining the initial void ratio of the sample.

After weighing the sample, the top glass plate was removed, and the small rubber "O" ring was placed over the beveled end of the sample holder. It was found that, by leaving the ring near the edge of the beveled section, it would remain on while the sample holder was being inserted into the osmometer. The holder was picked up from the lower glass plate and carbon disc, and inserted into the cathode end of the cylinder, and slowly pushed into position near the center of the osmometer. Extreme care was necessary in pushing the sample holder in order to prevent binding, displacement of the "O" ring, or damage to the sample. A large 4" rubber stopper on a metal rod just fit inside the cylinder and was used as a pusher to apply even pressure.

When the proper position was reached, the pusher was inserted in the anode end of the cylinder, and the sample holder was pushed back toward the cathode end. This caused the "O" ring to roll up the beveled edge of the sample holder and become firmly seated between the holder and the cylinder wall. The holder was at this time slightly nearer to the cathode end than it would be in its final position.

At this point the cathode was inserted into the cylinder and placed into position against the filter paper which covered the sample. The load bearing assembly was next

inserted. The cathode wire extended through the bearing assembly, and was connected into the circuit by means of the banana jack. The end plate was then bolted into position, and when the bolts were tightened the sample holder was pushed toward the anode side and assumed its correct final position with the cathode bearing firmly against the sample.

The osmometer was then turned on end with the anode end up. A filter paper was placed over this end of the sample. The left bearing assembly was inserted at this point for those tests run after it was constructed. The anode was then inserted against the filter paper, and the wire plugged into the circuit. The plunger was placed in contact with the anode face, and the left end plate bolted into position, with the deflection gauge attached to the outer face. The osmometer was then placed on the cradle, with the plunger through the self return bushing, which was not bolted down. The brass pointer was tightened in the correct position on the plunger.

The electrosmometer was now filled with water, and all possible entrapped air removed. The piezometer tube was screwed into position, and the water reservoir connected to the filling tube. After the thrust block and self return bushing were bolted into position, the load was applied to the plunger. The electrical wires from the osmometer were then connected to the terminals of the metering control unit, and the apparatus was ready for the actual test to begin.

E. Testing Procedure

Since some minor disturbance and rebound apparently occurred in the sample during the time that the sample and apparatus were being assembled, the apparatus was left standing after the load was applied until there was no further movement indicated on the compression dial. After the stable dial reading was reached, the water was raised in the piezometer tube to a height of 85-90 cm. above the constant level. The connecting tube was clamped shut, and the water allowed to flow back down the tube and through the sample so that the natural permeability might be determined before the test. The time required for a drop in head considered satisfactory varied from a few seconds for low clay content samples to several hours for those of high clay content.

After the final water height and time were recorded, the connecting tube was opened, so that the water level on both sides of the sample was equalized. The connecting tube clamp was closed again, and the apparatus was now ready for electrical testing.

The reservoir stopcock was adjusted to drip flow, then the current was turned on. The applied potential for all tests except one was set at a constant value of 2.7 volts. For the one exception, the voltage applied was half this figure, or 1.35 volts. Initial and subsequent periodic readings of time, current flow, height of rise in the piezometer tube, and compression dial were recorded throughout the test.

The tests continued until the maximum height of rise had passed, or until there was an overflow of the piezometer tube or other indications that normal electro-osmotic flow was no longer occurring.

Upon completion of the electro-osmotic test, the power was turned off at the power unit, and the current and voltage induced into the sample was determined by reversing the wires from the electrosmometer to the metering control unit. Samples of water from the anode side and the cathode side of the cylinder were taken by separately opening the drain tubes of the two sides. These water samples were used to determine the difference in pH values on the different sides of the soil sample after electrical treatment. The pH values were determined by using an electrically operated Beckman pH Meter, Model M, as manufactured by the National Technical Laboratories, South Pasadena, California.

After the pH test samples were taken, the water was completely drained from the cylinder. The apparatus was then dismantled, and the soil sample removed from the electrosmometer. Small portions of the sample were immediately taken from the anode face, the cathode face, and the middle part of the sample, and placed in weighing containers for moisture content determinations. A section of the sample was set aside for observation after drying. The remainder had a small amount of water added to it, after which it was thoroughly mixed to break up the structure which had been

formed during the test. It was then placed in an air-tight jar and allowed to set for a minimum period of 24 hours, after which post test Adderberg limits were determined. This completed the testing procedure for each sample.

PART VI.

RESULTS AND DISCUSSION

A. General

As has previously been indicated, there has been little uniformity in previous investigations and applications of electro-osmosis. This has been due not only to a lack of an organized overall program of research, but also to variations in aims and objectives, procedures, methods, equipment, and materials among different investigators. With this in mind, it was known from the outset of this investigation that there would be little opportunity for direct comparison or correlation of results obtained with those of other investigators. It was for this reason that the method of procedure adopted for this series of tests was intended to generally parallel that utilized by Wallace (28), and a portion of that utilized by Butler (4). In this way it was hoped that by utilizing similar methods and apparatus there would be some opportunity for comparison of results, and that this investigation might possibly assist in providing a basis upon which a continuing organized and correlated program of electro-osmotic research at Rensselaer Polytechnic Institute might be founded.

In order to obtain a better comparison with Wallace's results with illite, it was originally intended that a series of 9 tests using silver chloride electrodes

and varying kaolin - sand mixtures from 90% kaolin - 10% sand to 10% kaolin - 90% sand, with 10% incremental changes in each material, would be made. Also planned was one test with kaolin and the nickel silver electrodes used by Wallace, and one test with an illite-sand mixture and silver chloride electrodes. However, due to late arrival of some purchased materials, equipment breakdowns, and other unavoidable delays, it was possible to run only seven tests in the time available. These consisted of six tests with silver chloride electrodes, and one test with nickel silver electrodes. All samples were kaolin-sand mixtures.

Rather than a complete and detailed discussion of the results of each test individually, the results of the series of tests as a whole will generally be discussed. Discussion of results of individual tests will be limited to those points in which there is a deviation from general trends, or for other reasons individual discussion is deemed advisable. This method of discussion appears appropriate, since the results of all tests tend to follow a general pattern.

For brevity and ease of reference, the samples will be designated by a shortened numerical representation of the respective percentages of kaolin and sand. The first number in all cases will represent the percentage of kaolin. Thus, sample 90/10 means the sample consisting of a mixture of 90% kaolin and 10% sand. The designation 50/50 (a) in-

dicates the 50% clay - 50% sand sample in a test using silver chloride electrodes, whereas 50/50 (b) represents the same sample mixture using the nickel silver electrodes. Also for brevity and for uniformity, the use of the word "treatment" hereafter will refer to the application of the electrical potential to the sample so that electro-osmosis occurs, or the subjection of the sample to electro-osmosis for a period of time during the test.

A compilation of most of the results of this investigation is presented in Table 1. This table, the graphs of time vs. piezometer rise and current, and the raw data tabulations in the Appendix together provide a relatively complete summary presentation of the actual direct results of this investigation.

No post-test observations or determinations could be made on the 90/10 and 80/20 samples since these samples disintegrated in the electrosmometer due to movement of the sample holder under excessive pressure head during the tests.

B. Physical Appearance

Before mixing, the kaolin had a nearly white creamy appearance, and the sand was a light brown color. The samples then varied from an off white to a very light brown color, depending upon the clay-sand percentage mixture. After treatment during the tests, all samples were darker in color, with the greatest change in color being in

TABLE 1

Compilation of Test Data

Sample Kaolin/ Sand	Atterberg Limits -%						Moisture Content -%				$k_h \times 10^{-6}$ cm/sec		$k_e \times 10^{-6}$ cm^2/volt sec		Void Ratio at 0 Hr.
	Before			After			In-itial	Final							
	LL	PL	I_p	LL	PL	I_p		Anode	Mid.	Cath.	Before	After	Form.	Tan	
90/10	38.7	23.9	14.8	-	-	-	37.3	-	-	-	.234	-	-	20.08	.922
80/20	35.6	22.6	13.0	-	-	-	34.3	-	-	-	.276	-	-	18.62	.882
70/30	30.9	21.1	9.8	30.7	17.6	13.1	30.0	32.0	32.4	35.7	.148	.023	-	9.85	.798
50/50a	25.3	16.3	9.0	23.5	15.0	8.5	24.7	30.6	24.7	34.8	.600	.054	52.05	12.59	.678
50/50b	25.3	16.2	9.1	23.7	15.9	7.8	24.5	23.8	23.4	10.7	.262	.026	7.66	16.98	.657
20/80	18.2	NP	NP	14.8	NP	NP	NP	17.6	25.0	16.6	83.5	4.710	-	1.93	.473
10/90	16.0	NP	NP	NP	NP	NP	NP	19.3	19.8	19.6	7,750	17,330	0	0	.424

Note - The symbol "NP" indicates Non-Plastic - No limit obtainable.

the samples with high clay content that were tested with silver silver-chloride electrodes. The 50/50 (b) sample, which was treated with the nickel silver electrode, showed only a slight change in color, and less color change than the equivalent sample tested with the silver silver-chloride electrode.

Immediately after removal from the sample holder, the silver silver-chloride test samples had a definite blue-grey tint which was just a lighter shade of the color of the freshly chloridized electrodes. However, the blue-grey coloring was not uniformly distributed throughout the sample, particularly in the samples of high clay content. On the other hand, after these samples were allowed to dry, there was less indication of the blue-grey coloring, and the color of each sample was uniform throughout. The texture of these samples appeared to be uniform throughout, both when wet just after testing, and after drying.

The nickel silver test sample varied in color and texture in three distinct zones between the opposite faces, both immediately after testing, and after drying. At the cathode face there was a zone approximately .2" wide that appeared slightly darker and slightly more granular than before testing. Adjacent to this zone there was a narrow, but very distinct zone about .05" thick, that was very granular and much darker than the remainder of the sample. The zone appeared to be composed almost entirely of sand,

and was dark grey-green in color. The remainder of the sample showed very slight traces of green coloring, but not nearly as pronounced as in the narrow zone. The third and thickest zone extended to the anode face. This zone was only slightly darker than the zone at the cathode face, and not nearly as dark as the narrow inner zone. Also, the texture of the anodic zone was no different than before testing. There was very little cohesion between these zones, either when wet or dry, and the sample was easily separated along the inner zone. This laminated structure after treatment agrees with the results obtained by Butler (4), Tarran (24), and Wallace (28), in tests with illite and using the same nickel silver electrodes. This is also in agreement with Casagrande's (6) findings regarding laminated structure and reversion of clay samples to a more natural arrangement during electro-osmosis.

Except for the laminated 50/50 (b) sample, there appeared to be little difference in resistance to cracking between the fingers for the dry samples before and after treatment. There was also little difference between the action of the dry treated and untreated portions of sample 50/50 (b) when submerged in water. Both portions of the sample slumped and disintegrated within 5 minutes after being submerged. However, all samples treated with the silver silver-chloride electrodes, except the 10/90 sample, showed evidence of hardening as a result of treatment. When

the dry treated sample was submerged along with the dry untreated sample of the same clay content, the untreated samples in every case slumped and disintegrated within minutes. However, the treated samples retained their general shape after submergence for periods of 8 hours for the 20/80 sample to over 24 hours for the 70/30 sample. Due to lack of cohesion and small amount of clay, the 10/90 treated and untreated samples both disintegrated immediately upon being submerged.

Portions of each treated sample were wrapped in a piece of absorbent dry paper towel, and placed in an air tight jar for more than 24 hours, so that any loss of moisture from the sample would be into the towel. When removed from the jar, each towel was almost saturated with water absorbed from the sample. Those covering the silver silver-chloride samples were stained completely through to a dark grey-brown color. This was apparently from silver chloride that had been loosely deposited in the pores of the sample from the electrodes, and passed out of the sample with the water that flowed out by absorption into the towel. There was no appreciable change in color in the towel covering the nickel silver electrode treated sample. This indicates that there was less deposition of this electrode material, or that such material that was deposited was more tightly bound within the sample.

Further evidence of large amounts of loosely

bound silver chloride within the samples after treatment was indicated by the discoloration of the liquid limit device after post-test liquid limit determinations. The bowl was discolored from the normal shiny brass color to a dark grey-brown, which even vigorous scrubbing with scouring powder would not completely remove. The natural brass color was restored only after cleaning the bowl with dilute nitric acid.

C. Atterberg Limits

Before and after treatment values of Atterberg limit values are shown in Table 1. As was expected, the limit values decreased directly with decreases in kaolin content, both before and after treatment. Table 1 also indicates that there was a small decrease in each limit value after test. This agrees with the findings by Preece (19) and Shukla (22) of decreased limits, but the decreases in the current case are not as great. However, this is opposite to the findings of Christensen (11), and of Butler (4), Torran (24) and Wallace (28) using illite with nickel silver electrodes.

Table 1 further indicates conformity of results between silver silver-chloride and nickel silver electrodes, although there was slightly less decrease in limits when using nickel silver electrodes. It therefore appears that the Atterberg limit values for kaolin do not appreciably change after treatment. However, since this observation

is based on the use of only two different electrode materials, it is recognized that the use of some other electrode materials might possibly produce substantially different results.

D. Moisture Content

Moisture content values before test (initial), and aftet test (final) by sample zones, are shown in Table 1. The final determinations were made by zones in an attempt to show any changes in moisture content across the sample that might have occurred from electrical treatment.

Casagrande (9) has implied that samples should be near the liquid limit for tests of electro-osmosis. Table 1 shows that in every case except the 10/90 sample, the initial moisture content after preconsolidation and before treatment, was slightly below the liquid limit. The reason for the consistent relatively high moisture content for the 10/90 sample is not known. Wallace (28) postulates that higher moisture contents after treatment of a 20% clay, 80% sand sample was due to loss of clay from the sample into the water during the test, because of disturbance in the water. Even though there was a loss of clay noted from the 10/90 sample during natural permeability tests in the current study, this can not be advanced as a reason for the high moisture content, since the moisture content was even higher before testing.

The moisture content at the cathode face of the 50/50 (b) sample appears to be in error. It is possible that the porous cathodic zone of this sample, indicated in the previous subsection, may have drained considerably more than the remainder of the sample during the time when the apparatus was being dismantled and the sample removed, but is not considered likely that so much change can be attributed to such drainage.

Considering the samples treated with silver silver-chloride electrodes, the 70/30 and 50/50 samples, which contained appreciable amounts of clay, exhibited increased moisture content after treatment, with the greatest increase at the cathode face. The 20/80 and 10/90 samples, with inappreciable clay content, exhibited smaller moisture content values at the anode and cathode faces after treatment than for the sample as a whole before treatment. It was noted that due to their relatively porous structure and small clay content, both these samples lost a portion of their clay content during natural permeability testing. It is considered possible that each of these samples contained greater moisture contents immediately after electrical testing than the initial values, but that a portion of this water was lost by drainage while the samples were being removed from the sample holder. If this condition is the one that actually existed, then it would appear that the treatment of a kaolin-sand mixture with silver silver-chloride

electrodes, and in an electrosmometer in which there is a continuous head of water on each side of the sample, produces an increase in the moisture content of the sample. However, this is contrary to the findings of other investigators (4, 9, 28) with different sample and electrode materials. For this reason, and because of the variable values obtained, it is felt that any conclusions drawn from these tests regarding the effect of treatment on the moisture content of the samples would be mere speculation. Thus these results are considered to be non-conclusive.

E. Hydraulic Permeability

Values for hydraulic permeability, k_h, obtained before and after treatment, are shown in Table 1. It can be noted that generally the permeability values obtained increased with decreases in clay content, as was expected. However, the value for the 70/30 sample is less than those for the samples of greater clay content. A possible explanation for this variance from the normal trend, lies in the longer preconsolidation loading time for this sample. All other samples were pre-loaded for a period of 5 or 6 days, whereas the 70/30 sample was subjected to the load for a period of 21 days prior to test because of a change in the planned sequence of tests.

The longer loading period undoubtedly produced less free pore space for the water to pass through, even though

the void ratio of this sample, as indicated by Table 1, was not out of line in comparison to the other samples. This is considered possible because the sample was kept in contact, at both top and bottom, with a supply of water throughout the preloading period. Thus the clay particles may have become more hydrated, such that the additional thickness of adsorbed water tended to constrict the flow of free water during the permeability test. If this additional adsorbed water consisted of planar water (1), adsorbed by the unsaturated valences on the surface of the kaolin lattice, it would have been comparatively loosely held, even though sufficient to restrict flow of free water. Thus it could still have been driven off at 110° C. during initial moisture content determination, thus not affecting the void ratio value, which was obtained through use of this initial moisture content value.

Except for the 10/90 sample, all samples tested with the silver silver-chloride electrodes had higher values of hydraulic permeability before treatment than after treatment. The values ranged from 6.5 times as great before treatment for the 70/30 sample to 17.6 times as great in the case of the 20/80 sample. It is believed that the primary reason for the reduced permeability lies in the deposition of electrode material within the sample during treatment. As indicated under Physical Appearance, above, there is ample indication that decomposed electrode materials exist

within the samples after treatment.

A number of other investigators have found that permeability was decreased after treatment. Geuze, de Bruyn, and Joustra (14) attribute it to electro-chemical phenomena, probably caused by the flocculating power of the anode cupric ions on the negatively charged colloidal soil particles, and possibly by the formation of insoluble copper compounds within the sample due to the copper anode used. Casagrande (9) attributes the reduced permeability to a decrease of the hydraulic gradient as a result of consolidation of the clay by electrical treatment.

The 10/90 sample indicated a higher value of hydraulic permeability after treatment. However, this is obviously an erroneous indication, since it was noticed that a considerable amount of the clay was washed out of the sample during the permeability tests, both before and after treatment. Thus, in effect, the permeability test after treatment was on a sample of less clay content, in which a greater permeability could be expected.

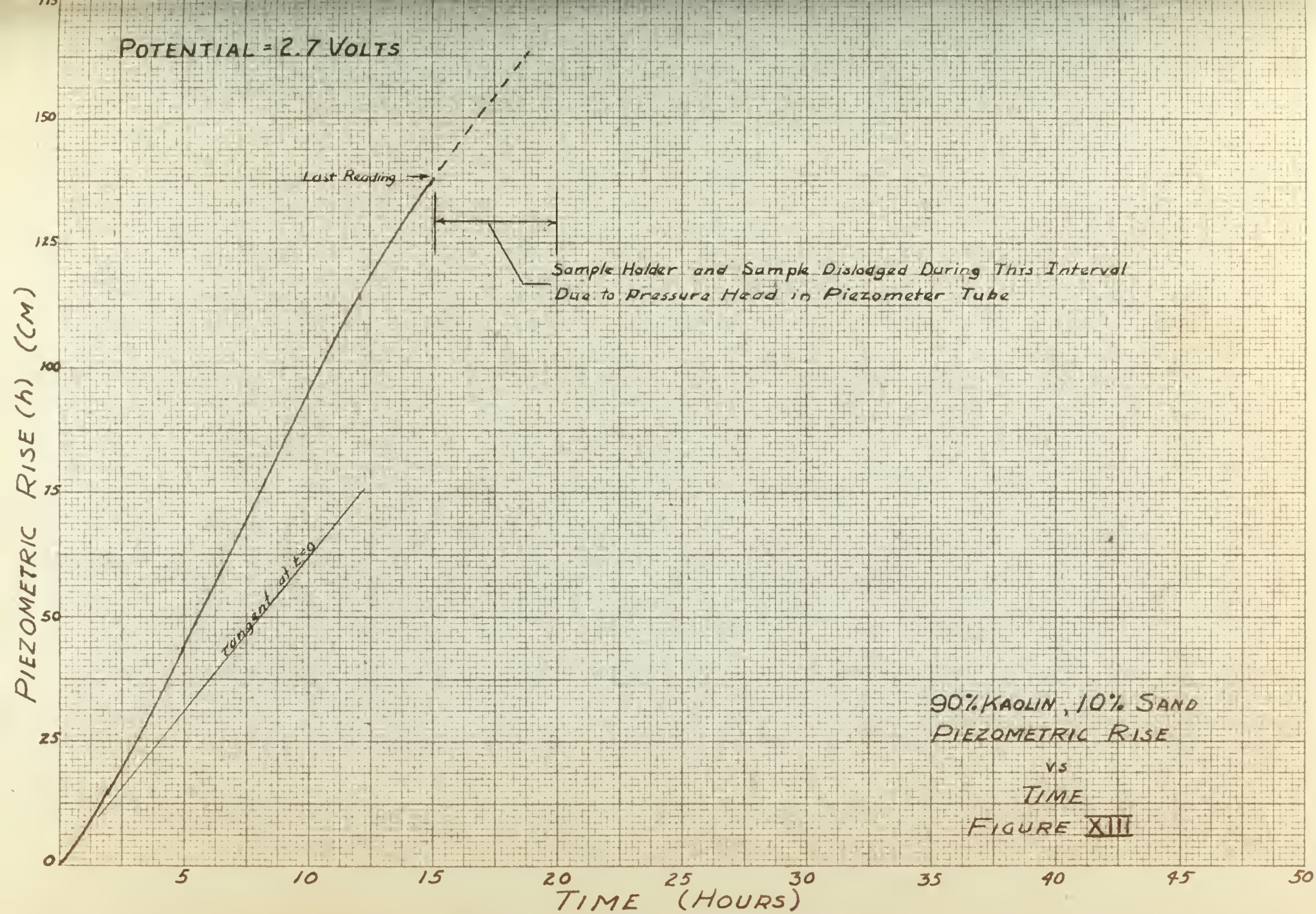
For the 50/50 (b) sample, which was treated with the nickel silver electrodes, permeability values obtained before and after treatment were less than those on an equivalent sample treated with silver silver-chloride electrodes. This was not entirely unexpected because, even though the electrodes were porous, no flow paths were visible through them, and they did not appear as though they would permit

as free flow of water through them as appeared to be possible through the perforated silver silver-chloride electrodes. Since the values obtained with the latter perforated electrodes were in each case a little more than two times as great, it is felt that the difference in values obtained with the different electrodes on comparable samples is purely a function of the relative porosities of the different electrodes.

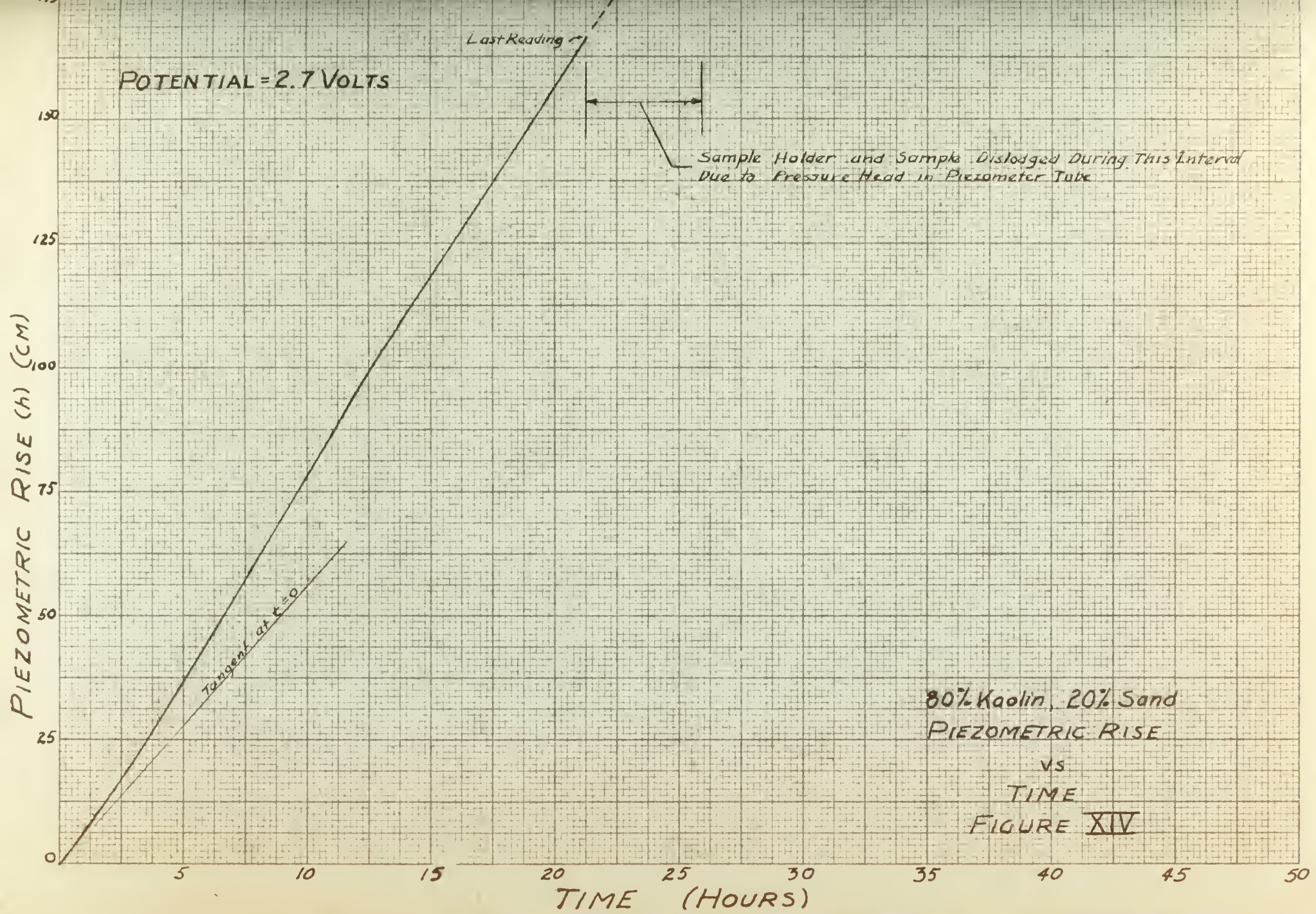
No post-treatment permeability tests were possible with the 90/10 and 80/20 samples because the samples were destroyed when the sample holder moved within the cylinder.

F. Piezometric Height of Rise and Electro-Osmotic Permeability

Two methods of determining the electro-osmotic permeability of a soil sample were indicated under Theory in Part III. Both methods are dependent on the height of rise of water in a piezometer tube induced by electrical treatment. Because of this close relationship between these two factors, they will be discussed under the same heading. Values of electro-osmotic permeability obtained through the use of the formula and the maximum height of rise, when obtainable, and those obtained through the use of the slope of the tangent line to the piezometer rise vs. time curve at zero time, are given in Table 1. The height of rise vs. time curves, with the corresponding tangent lines at zero time superimposed, are shown in Figures XIII through XVIII.



90% KAOLIN, 10% SAND
PIEZOMETRIC RISE
VS
TIME
FIGURE XIII



80% Kaolin, 20% Sand
PIEZOMETRIC RISE
vs
TIME
FIGURE XIV

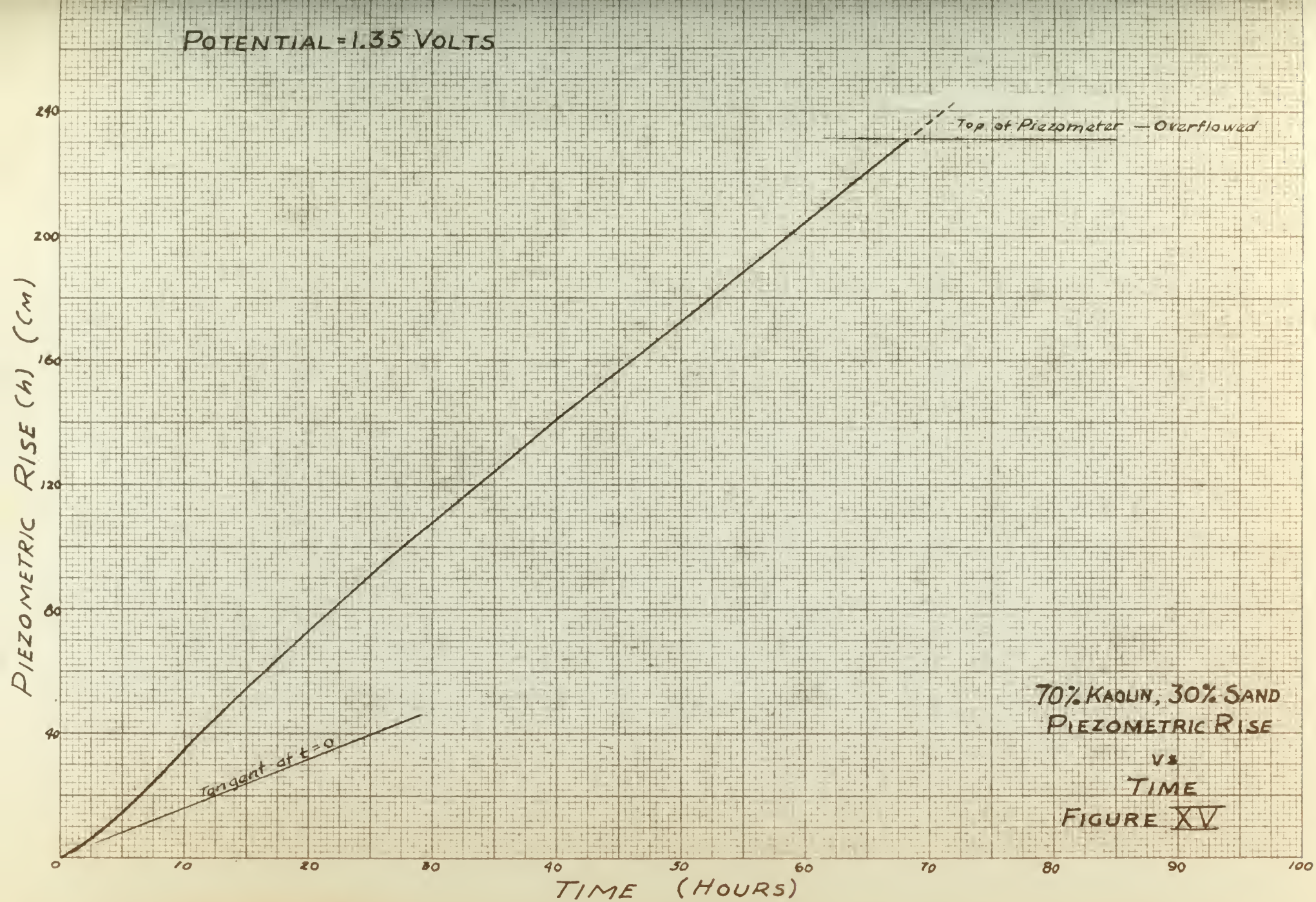
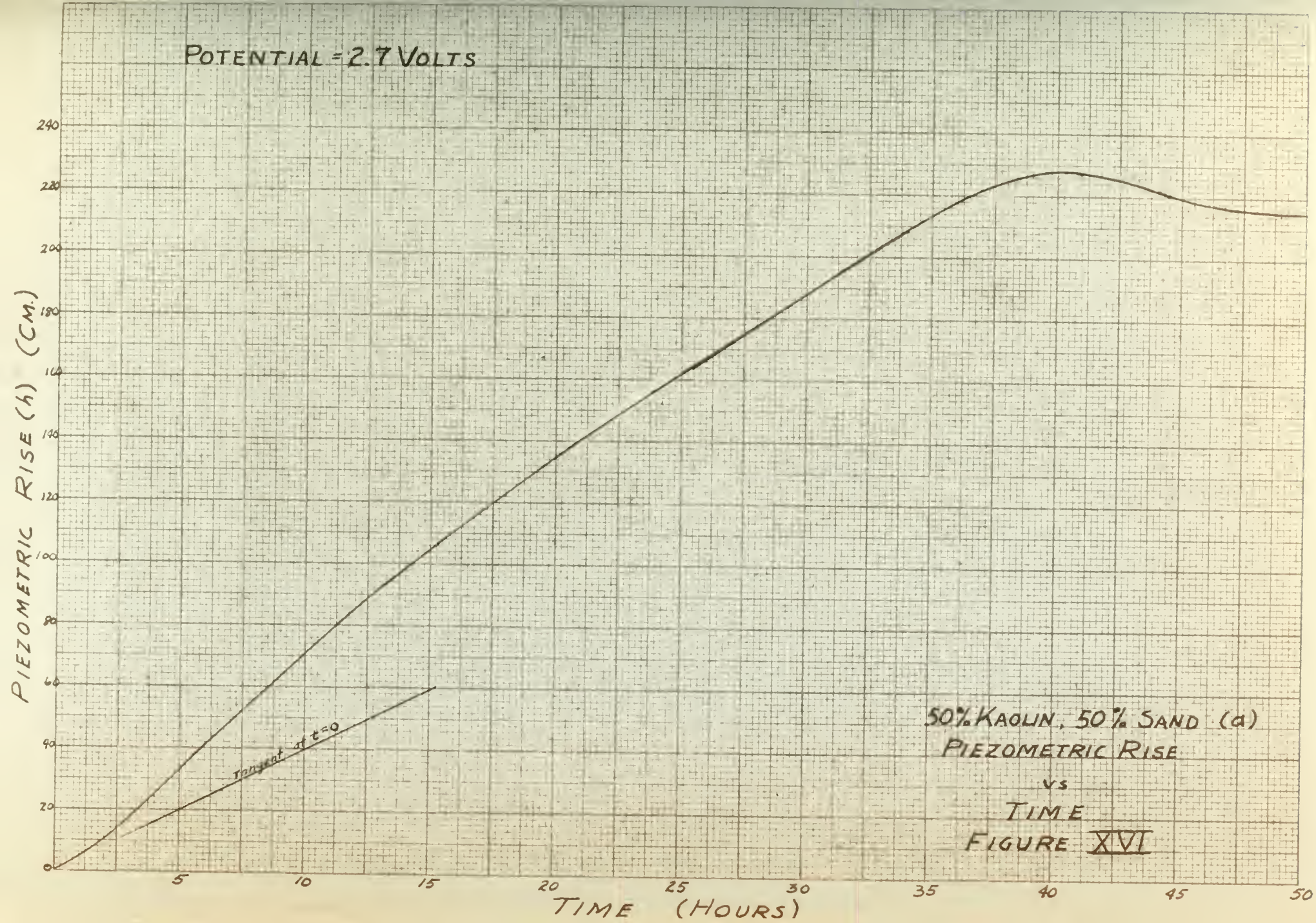
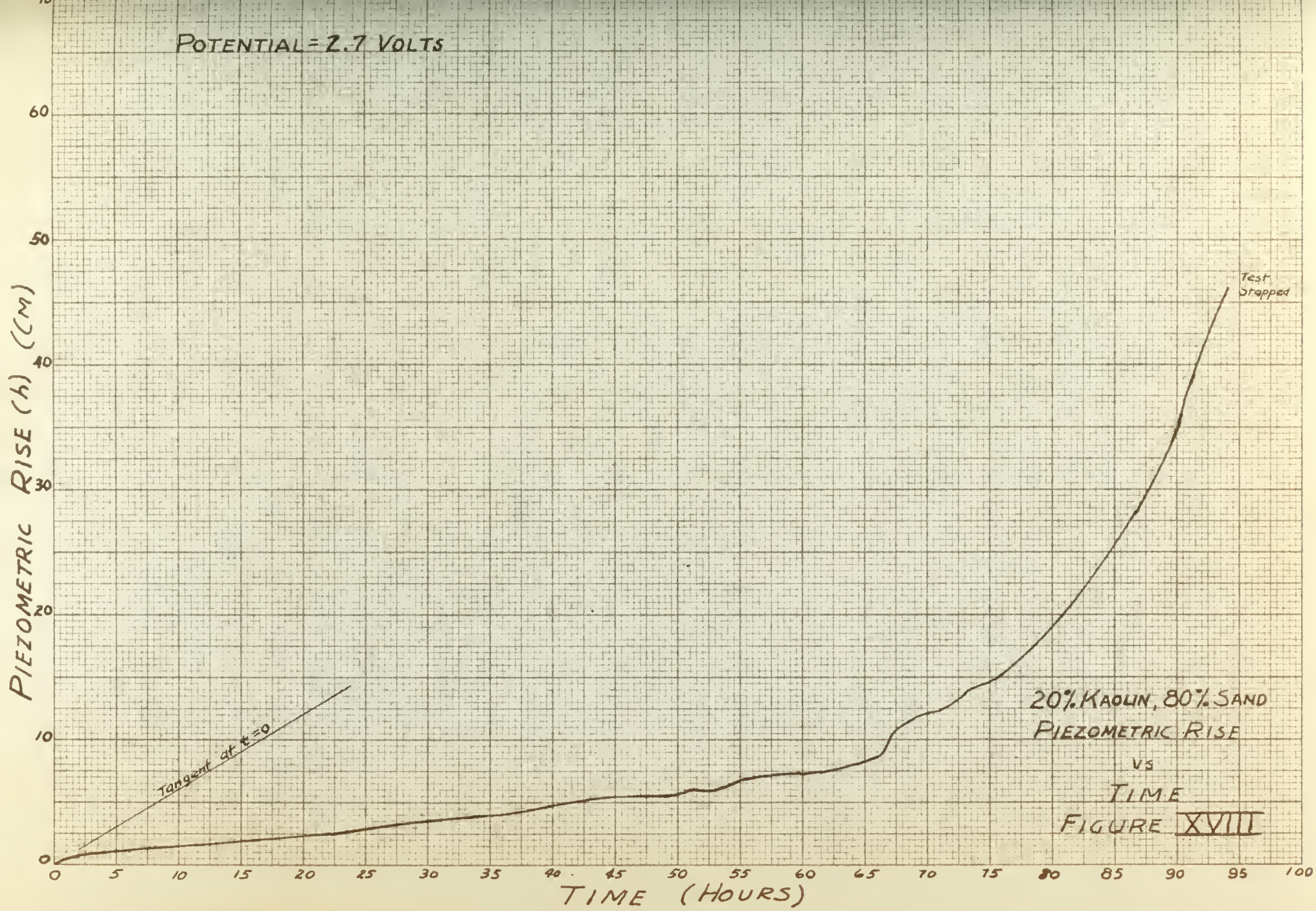

POTENTIAL = 1.35 VOLTS
Top of Piezometer — Overflowed
Tangent at t = 0
PIEZOMETRIC RISE (h) (CM)
TIME (HOURS)
0
10
20
30
40
50
60
70
80
90
100
40
80
120
160
200
240
70% KAOLIN, 30% SAND
PIEZOMETRIC RISE
vs
TIME

FIGURE XV


POTENTIAL = 2.7 VOLTS
PIEZOMETRIC RISE (h) (CM.)
0
20
40
60
80
100
120
140
160
180
200
220
240
TIME (HOURS)
5
10
15
20
25
30
35
40
45
50
Tangent at t=0
50% KAOLIN, 50% SAND (a)
PIEZOMETRIC RISE
vs
TIME
FIGURE XVI

50% KAOLIN, 50% SAND (b)
PIEZOMETRIC RISE
vs
TIME
FIGURE XVII



20% KAOLIN, 80% SAND
PIEZOMETRIC RISE
VS
TIME
FIGURE XVIII

No curve for the 10/90 sample is shown because no rise was achieved during the test.

Values of maximum height of rise were obtained for the 50% kaolin samples only. In all cases of greater clay content, the maximum height of rise either exceeded the height of the piezometer tube, or obviously would have except for loss of the sample during the test.

The greatest height of rise previously obtained with the electrosmometer was 124 cm, obtained by Butler (4) with a 100% clay (illite) sample. The greatest rise obtained by Wallace with an illite-sand mixture was 58 cm with the 90/10 sample. Therefore, the comparatively high heights of rise obtained were not anticipated prior to the initial test.

During the first two tests, with 90/10 and 80/20 samples, the samples were lost when the height reached an estimated value of approximately 175 cm. The cause and manner of the displacement of the sample holder and samples was not immediately obvious because the apparatus was unattended at the time of failure in each case. However, after the second failure and a careful analysis of the electrosmometer, it became apparent that there was insufficient lateral support for the sample holder to prevent its displacement in the direction of the anode under the pressure heads of the abnormally high heights of rise being obtained. The left bearing plate was then fabricated to provide positive bearing against the left end plate, and

thus prevent further sample holder displacements.

It also became obvious that either the kaolin was considerably more susceptible to electro-osmotic flow than illite, or that the silver silver-chloride electrodes were considerably more active in producing electro-osmotic flow than were the nickel silver electrodes. The 50/50 (b) test results indicate that both these conditions apply to some degree. This is indicated by the fact that the kaolin-sand sample and nickel silver electrodes produced a height of rise which was approximately twice as great as was produced by the same percentage of illite and the same electrodes. Further evidence is provided by the fact that the silver silver-chloride electrodes produced a height of rise approximately 4 times as great as was produced with the same percentage of kaolin with the nickel silver electrodes.

Not only was the maximum height of rise 4 times as great, but the electro-osmotic coefficient of permeability, k_e, obtained from the formula and maximum height of rise, was approximately 7 times as great with the silver silver-chloride electrodes.

Except for the 70/30 sample, all those treated with the silver silver-chloride electrodes produced values of k_e which were inversely proportioned to the kaolin content. The 70/30 sample gave a value which was lower than that obtained with the 50/50 sample. Here again it is believed that the fact that the k_e value is out of line when

compared to the other samples, is as a result of the longer preloading time for this sample. It is to be noted that the values of both the hydraulic and electro-osmotic coefficients of permeability for the 70/30 sample are slightly greater than half the values for the 80/20 sample.

For the 70/30 sample, which was cronologically the last test run, it was decided to use only half the potential gradient used in all other tests. The potential for this test was then 1.35 volts. Thus, undoubtedly, the lower value of k_e obtained for this sample was due to the lower applied potential. However, even with the lower potential gradient, the height of rise obtained was so great that it overflowed the top of the piezometer tube, which extended to a height of 231.3 cm. above the constant head. When overflow occurred, the tube to the anti-evaporation apparatus was disconnected at the funnel, and inserted into a 100 cc graduate, so that the quantity of overflow might be checked. It was found that the rate of discharge for a period of thirty hours after overflow was identical with the rate of flow calculated from the rate of rise for 30 hours prior to overflow.

It should be noted that there was no noticeable gas formation in the cylinder when using the silver silver-chloride electrodes, and thus there was no difficulty in reading the height of rise. However, in the test using nickel silver electrodes, the same difficulties in obtaining

accurate readings reported by other investigators were experienced.

G. Applied Potential

The potential applied in all tests except with the 70/30 sample was 2.7 volts. This value was selected to conform to the potential applied by Wallace (28). However, since the carbon disc spacer placed in the sample holder when emplacing the sample was thinner than the one used by Wallace, the samples in the current tests were slightly thicker than those of Wallace. For this reason, the potential gradients were lower, and varied from 1.15 to 1.36 for the 2.7 volt applied potential, and was .68 for the 1.35 volt applied potential.

H. Current Changes

The current flowing generally was at or near its maximum value at the beginning of the test. It tended to rise slightly the first few minutes, then decrease fairly rapdily until 5 to 7 hours after the beginning of the test, then smooth out into fairly steady flow. Curves of current flowing vs. time are shown in Figures XIX through XXII. It can be seen that there was no significant trend regarding the maximum current flow and the clay content of the samples. However, there was a greater drop in current to the comparatively steady rate with decreases in clay content of the samples.

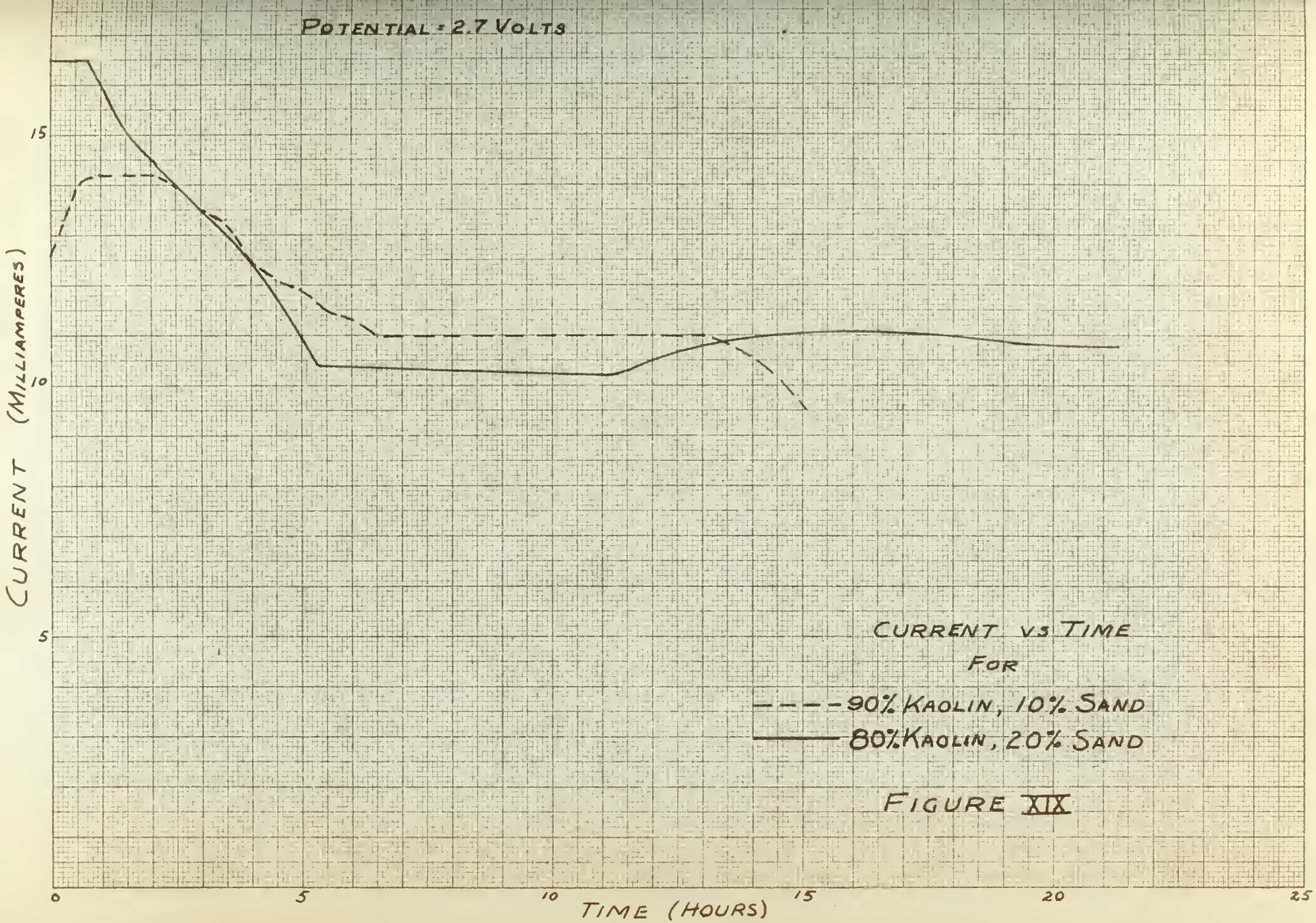
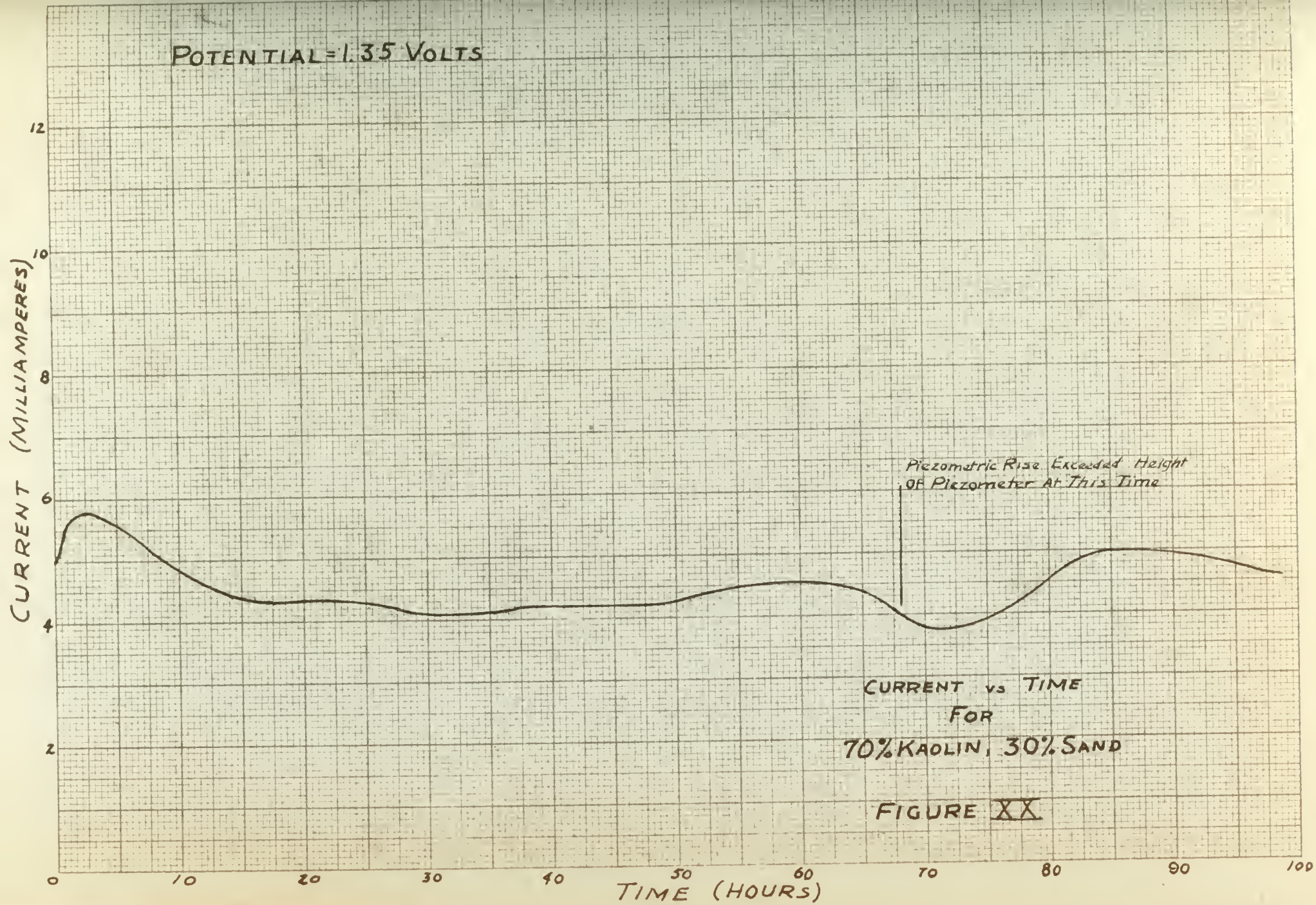
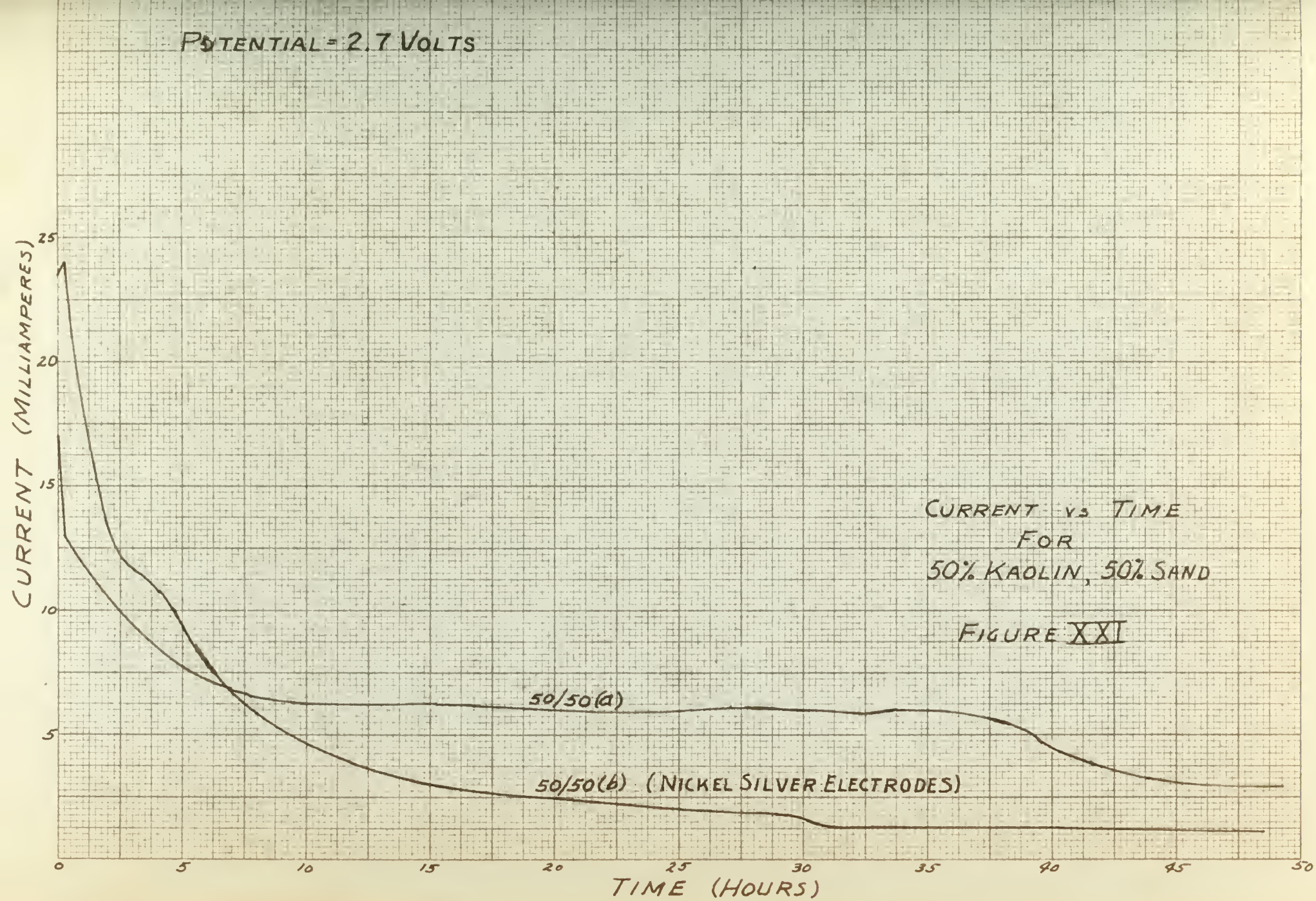

POTENTIAL = 2.7 VOLTS
CURRENT (MILLIAMPERES)
15
10
5
0
5
10
15
20
25
TIME (HOURS)
CURRENT VS TIME
FOR
90% KAOLIN, 10% SAND
80% KAOLIN, 20% SAND

FIGURE XIX



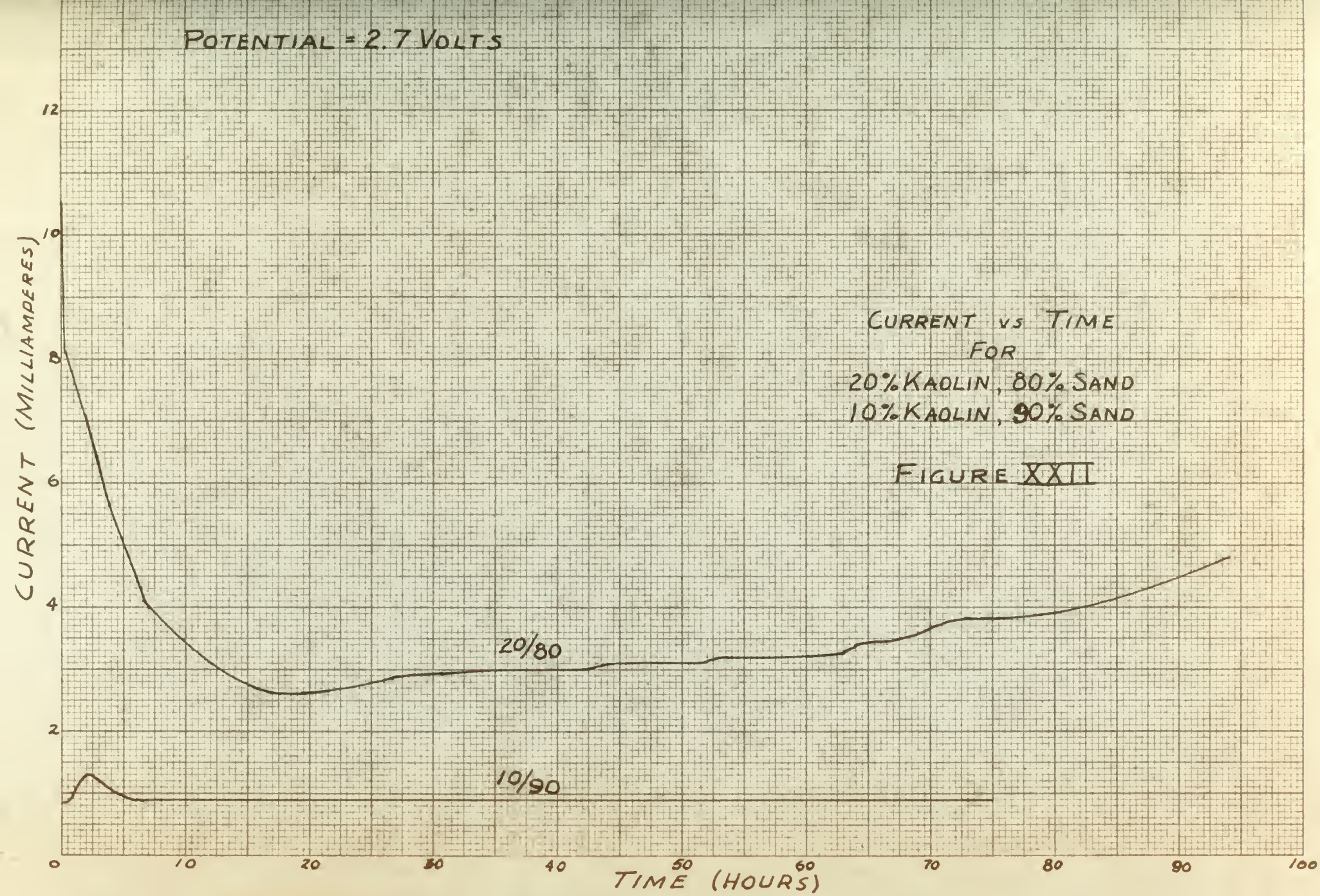
CURRENT vs TIME
FOR
70% KAOLIN, 30% SAND

FIGURE XX



CURRENT vs TIME
FOR
50% KAOLIN, 50% SAND

FIGURE XXI


POTENTIAL = 2.7 VOLTS
CURRENT (MILLIAMPERES)
12
10
8
6
4
2
0
10
20
30
40
50
60
70
80
90
100
TIME (HOURS)
20/80
10/90
CURRENT VS TIME
FOR
20% KAOLIN, 80% SAND
10% KAOLIN, 90% SAND
FIGURE XXII

The rapid and fairly large drop in current flow early in the test, followed by comparatively steady flow, agrees with the results obtained by Wallace. This is in spite of findings by Casagrande (6) that a noticeable decrease in current flow occurs only after the water content has been reduced to a state far below the magnitudes which have any application in building practice. As has previously been noted, there was no indication of substanital reduction in water content within the samples.

I. Changes in Electrodes

Measurements of weight and thickness of the electrodes used were made before and after each test in order to determine the changes that might take place during the test. Results of the weight measurements are shown in Table 2. Electrode thicknesses are not tabulated, since the thicknesses varied considerably across the surfaces of the electrodes. The greatest thickness in each case occurred in the vicinity of the electrode wires, and gradually decreased from this area. The greatest decrease in thickness during the tests occurred in the central portion of the electrodes - the area of the anode in contact with the plunger, and the area of the cathode in contact with the sample.

It should be noted that both the anode and cathode decreased in weight during each test, with the greatest decrease occurring in the anode. This does not agree with the

TABLE 2

Electrode Weights

Sample Kaolin/ Sand	Anode Weight (gm)			Cathode Weight (gm)		
	Before	After	Loss	Before	After	Loss
90/10	27.338	24.774	2.564	70.427	69.852	.575
80/20	27.437	25.731	1.706	68.286	- -	- -
70/30	27.729	25.481	2.248	58.753	58.203	.550
50/50 a	23.987	22.788	1.199	70.856	70.668	.188
50/50 b*	47.287	47.052	.235	140.439	140.402	.037
20/80	25.198	24.032	1.166	63.845	63.495	.350
10/90	20.994	20.717	.277	64.752	64.645	.107

*Note - The 50/50 (b) sample was tested with nickel silver electrodes. All others with silver silver-chloride electrodes.

results obtained by Wallace (28) with illite and nickel silver electrodes. In Wallace's investigation after each test, the anode had decreased in weight, and the cathode had increased in weight by a small amount, but the increase at the cathode was not equal to the decrease in anode weight. Since the nickel silver cathode weight increased during each test with illite, while the silver silver-chloride and the nickel silver cathodes both decreased in weight during tests with kaolin, it appears patent that in the electro-osmotic treatment of clay-sand mixtures, whether the net change in electrode weights is a gain or a loss, depends, at least in part, upon the nature of the clay being treated. It also appears evident from these tests that the amount of electrode weight change during the electro-osmotic treatment of a particular sample depends upon the material constituents of the electrodes.

J. pH Values

The pH value of the water from each side of the cylinder was determined at the conclusion of each test except for the 80/20 sample. For the tests with silver silver-chloride electrodes, the values obtained when electro-osmotic flow had been produced were greater on the anode side than on the cathode side. Values obtained from each side were lowest for the extreme high and low kaolin content samples, and highest for the median 50/50 percentage sample.

The range of values for the anode side was 5.40 to 7.20, and for the cathode side it was 5.28 to 6.70. For the 10/90 sample, in which no electro-osmotic flow was produced, the pH trend was reversed. The values obtained from the anode and cathode sides were 5.93 and 6.67, respectively.

For the 50/50 (b) sample, which was treated with the nickel silver electrodes, the pH values were also reversed from those of the other electro-osmotic flow producing samples. This agrees with the findings of Wallace (28), who also obtained higher cathode side values when using the nickel silver electrodes with illite. The values obtained with the 50/50 (b) sample were also in close agreement with the range of values obtained by Wallace. The value for the anode and cathode faces were respectively 6.20 and 10.80, where Wallace's values had a 5.7 - 6.1 anode range and a 10.65 - 10.8 cathode range. This indicates there is little difference in the pH values produced with kaolin and illite when using electrodes of the same material, but that silver silver-chloride electrodes produce values which are considerably lower than those produced by nickel silver electrodes.

K. Changes in Sample Thickness and Void Ratio

There was no significant indication of change in sample thickness or consolidation from the results obtained during these tests. The only trend appearing was that the

compression dial readings generally indicated a small amount of expansion in the sample during the early portion of the tests, followed by a small decrease in thickness to a minimum at about the time that the heights of rise were around 60-70 cm. For heights of rise in excess of this general range, the dial readings indicated expansion of the samples again.

It is not known whether there was actually an expansion occurring in the samples, or whether the higher heights of piezometric rise produced pressure heads tending to offset the force from the loading assembly, and thus produce movement of the samples rather than the expansions indicated by the dial readings. It is felt that the latter is definitely the case, at least to some extent, when the height of piezometric rise exceeded 150 cm.

Since no definite determinations could be made regarding changes in sample thickness, only the initial values for void ratio were tabulated. These are shown in Table 1.

L. Induced Electrical Forces in the Sample

At the conclusion of each test, after turning off the power and reversing the leads, it was found that a measurable voltage had been induced into the sample-electrode system. The voltage varied from .1-.2 volt and the current from .25-.50 ma. for the sample treated with silver silver-chloride electrodes. The highest values were obtained from

the samples of greatest clay content. For the sample treated with nickel silver electrodes, the voltage was .2 volt and the current was .8 milliampere. These values gradually decreased until they were approximately half the initial values after a 24 hour period of observation. However, in the case of the silver silver-chloride electrodes, the values for each sample dropped to approximately .05 volt and .1 ma. after one hour, then remained steady for a maximum observation period of 6 hours.

It was noted that the values of induced electrical forces obtained in these tests with kaolin-sand samples were lower than those obtained by Wallace (28) with the illite-sand samples. Wallace's values ranged from .2 - .7 volts and from 1.3 - 4.5 milliamperes.

PART VII.

CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

The conclusions to be presented here are primarily of a general nature, and are based entirely on the results obtained and observations made during the series of tests that formed the basis of this investigation. More detailed conclusions would have been desirable. However, any conclusions must be geared to the conditions and limitations of the tests from which they are derived. Some of the limiting conditions affecting the conclusions from these tests are the relatively short period of time available for the investigation, the limited number of tests conducted, and the physical shortcomings of the equipment for providing conclusive results regarding some factors investigated.

Some of the conclusions from this investigation conform to those of other investigators regarding electro-osmosis. Those that might not conform are nevertheless considered valid for the particular conditions, equipment, and materials for the tests conducted in this investigation.

The following are the conclusions reached.

1. Kaolin-sand mixtures containing at least 20% kaolin are susceptible to electro-osmotic flow under an applied electrical potential.

2. The application of an external electrical

potential to a kaolin-sand mixture containing an appreciable percentage of kaolin produces an electro-osmotic coefficient of permeability which is considerably greater than the hydraulic permeability. Thus, a natural kaolin-sand deposit will generally be much easier drained by electro-osmosis than by natural drainage.

3. The electro-osmotic permeability of a kaolin-sand mixture depends on the electrode materials, and is directly proportional to the kaolin content for electrodes of a particular material.

4. Silver silver-chloride electrodes are highly conducive to the production of electro-osmotic flow, and are more conducive than nickel silver electrodes to the production of electro-osmotic flow in similar kaolin-sand mixtures.

5. Electro-osmotic treatment of a kaolin-sand mixture with either silver silver-chloride or nickel silver electrodes results in lower Atterberg limit values than for like untreated mixtures.

6. Electro-osmotic treatment of a kaolin-sand mixture reduces the hydraulic permeability of the mixture.

7. The electro-osmotic treatment of a kaolin-sand sample in an electrosmometer with nickel silver electrodes changes the structure of the sample into three distinct zones normal to the flow path.

8. Electro-osmotic treatment of a kaolin-sand

mixture in an electrosmometer and under a 1/4 T/ft.^{2} does not produce appreciable consolidation of the mixture.

9. Kaolin-sand mixtures are more susceptible to electro-osmotic flow than similar illite-sand mixtures.

10. Permanent hardening of kaolin-sand mixtures is not produced by electro-osmotic treatment with nickel silver electrodes, but some hardening is produced by silver silver-chloride electrodes.

11. Electro-osmotic treatment of a kaolin-sand mixture with silver silver-chloride electrodes results in greater pH values in the water in the vicinity of the anode than in the vicinity of the cathode, whereas treatment with nickel silver electrodes produces higher pH values in the vicinity of the cathode.

12. The application of an externally applied electrical potential to a kaolin-sand mixture during electro-osmosis results in small but measurable induced potential and current flow which are opposite to the direction of the applied potential and current flow.

B. Recommendations

The basic recommendation to be made is that further research involving electro-osmosis be conducted at Rensselaer Polytechnic Institute. There are any number of phases of the subject which might be investigated, and any number of different types of tests which might be conducted. However,

only a few general recommendations will be made here.

It is recommended that additional tests be conducted on the equipment used in this investigation. The tests should include additional use of the silver silver-chloride electrodes with clays of the other major groups as well as kaolin. In this way, better comparisons of the relative effects of electro-osmosis on the different clays should be obtained.

Tests similar to those of this study, but with various potential gradients for any one sample would be desirable, and provide useful information regarding possible optimum gradients.

Tests of known mixtures of more than one clay would approach conditions in natural soils, and provide a better understanding of the effects of electro-osmosis on natural fine grained soil deposits.

The only recommendation regarding the electrosmometer is that a piezometer tube of greater cross-sectional area be installed for tests using silver silver-chloride electrodes, in order to prevent overflow from heights of piezometric rise in excess of the height of the tube.

PART VIII.

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APPENDIX

RAW DATA FOR EACH TEST

TABLE 3

Raw Data

Sample: 90% Kaolin, 10% Sand
Type of Electrode: Silver Silver-Chloride
Voltage Between Electrodes: 2.7 Volts
Sample Thickness at 0 Hours: 2.272 cm
Specific Gravity: 2.610

Date	Time	Hours	Current (ma)	Ht. of Rise (cm)	Comp. Dial Reading (in)
3/22/58	0930	0.0	12.6	0.0	.1741
	0945	.25	13.3	1.5	.1740
	1000	.50	13.9	3.1	.1739
	1015	.75	13.7	4.9	.1734
	1030	1.0	14.2	6.7	.1730
	1100	1.5	14.2	10.8	.1720
	1130	2.0	14.2	15.3	.1710
	1200	2.5	14.0	19.9	.1702
	1230	3.0	13.5	24.9	.1700
	1300	3.5	13.3	29.9	.1700
	1330	4.0	12.5	34.9	.1702
	1400	4.5	12.1	39.8	.1712
	1500	5.5	11.5	49.9	.1741
	1600	6.5	11.0	60.0	.1765
	1700	7.5	11.0	69.5	.1789
	2230	13.0	11.0	119.9	.1788
3/23/58	0106	15.6	9.5	138.3	.1752

TABLE 4

Raw Data

Sample: 90% Kaolin, 10% Sand
Type of Electrode: Silver Silver-Chloride
Voltage Between Electrodes: 2.7 Volts
Sample Thickness at 0 Hours: 2.34 cm
Specific Gravity: 2.622

Date	Time	Hours	Current (ma)	Ht. of Rise (cm)	Comp. Dial Reading (in.)
3/28/58	2200	0.0	16.5	0.0	.1480
	2215	.25	16.5	1.4	.1472
	2230	.50	16.5	3.1	.1462
	2245	.75	16.5	4.8	.1452
	2300	1.0	16.0	6.7	.1444
	2330	1.5	15.0	10.2	.1430
	2400	2.0	14.5	13.9	.1421
3/29/58	0100	3.0	13.5	21.6	.1407
	0200	4.0	12.5	29.6	.1407
	0300	5.0	11.0	37.8	.1413
	0636	8.6	10.3	68.1	.1491
	0900	11.0	10.2	87.9	.1488
	1000	12.0	10.6	95.3	.1474
	1200	14.0	11.0	111.0	.1440
	1400	16.0	11.0	126.0	.1440
	1700	19.0	10.9	148.8	.1334
	1918	21.25	10.8	165.8	.1325

TABLE 5

Raw Data

Sample: 70% Kaolin, 30% Sand
Type of Electrode: Silver Silver-Chloride
Voltage Between Electrodes: 1.35 Volts
Sample Thickness at 0 Hours: 1.985 cm
Specific Gravity: 2.635

Date	Time	Hours	Current (ma)	Ht. of Rise (cm)	Comp. Dial Reading (in)
4/28/58	0900	0.0	5.0	0.0	.2840
	0930	.5	5.25	0.9	.2840
	1000	1.0	5.6	2.0	.2843
	1100	2.0	5.7	4.7	.2843
	1148	2.8	5.8	7.4	.2842
	1300	4.0	5.7	11.2	.2842
	1400	5.0	5.6	14.9	.2841
	1500	6.0	5.4	18.8	.2842
	1712	8.2	5.0	27.5	.2843
	2000	11.0	4.7	39.1	.2846
	2200	13.0	4.5	46.7	.2850
	2312	14.2	4.4	51.3	.2850
4/29/58	0012	15.2	4.4	55.2	.2850
	0100	16.0	4.4	58.2	.2850
	0206	17.1	4.3	62.4	.2850
	0900	24.0	4.3	87.7	.2848
	1115	26.25	4.2	95.6	.2844
	1300	28.0	4.1	101.3	.2841
	1530	30.5	4.1	109.6	.2839
	1706	32.1	4.1	114.9	.2835
	2018	35.3	4.1	125.8	.2830
	2200	37.0	4.2	131.4	.2829
	2400	39.0	4.2	138.0	.2824
4/30/58	0900	48.0	4.2	167.3	.2798
	1000	49.0	4.2	170.1	.2795
	1430	53.5	4.4	183.9	.2789
	1606	55.1	4.4	188.9	.2781
	1915	58.25	4.4	199.3	.2768
	2215	61.25	4.5	209.0	.2746
5/1/58	0036	63.6	4.5	216.4	.2729
	0106	64.1	4.4	217.8	.2718
	1000	73.0	3.8	over-flowing	.2332

TABLE 6

Raw Data

Sample: 50% Kaolin, 50% Sand (a)
Type of Electrode: Silver Silver-Chloride
Voltage Between Electrodes: 2.7 Volts
Sample Thickness at 0 Hours: 2.022 cm
Specific Gravity: 2.659

Date	Time	Hours	Current (ma)	Ht. of Rise (cm)	Comp. Dial Reading (in)
4/12/58	1000	0.0	17.0	0.0	.2712
	1015	.25	13.0	0.9	.2712
	1030	.50	12.6	2.2	.2712
	1045	.75	12.3	3.7	.2712
	1100	1.0	11.9	5.2	.2712
	1130	1.5	11.1	8.3	.2711
	1200	2.0	10.5	11.5	.2710
	1230	2.5	9.7	15.1	.2709
	1300	3.0	9.2	18.6	.2708
	1400	4.0	8.3	26.3	.2707
	1500	5.0	7.6	34.6	.2708
	1700	7.0	6.8	49.0	.2710
	1930	9.5	6.4	66.7	.2712
	2100	11.0	6.3	77.7	.2713
	2400	14.0	6.3	97.5	.2713
4/13/58	0100	15.0	6.3	103.9	.2715
	0800	22.0	6.0	145.5	.2695*
	1000	24.0	6.0	156.5	.2685*
	1200	26.0	6.1	166.6	.2672*
	1400	28.0	6.2	176.9	.2660*
	1700	31.0	6.0	192.4	.2627*
	1900	33.0	5.9	202.4	.2605*
	2200	36.0	5.8	216.9	.2541*
	2400	38.0	5.5	224.8	.2270*
4/14/58	0130	39.5	4.7	227.5	.1830*
	0848	46.8	2.9	217.7	.0540*
	1112	49.2	2.9	214.4	.0100*
	1300	51.0	3.0	214.7	.0082*
	1500	53.0	3.5	218.7	- .0090*

* Readings influenced by movement of sample holder and sample under pressure head

TABLE 7

Raw Data

Sample: 50% Kaolin, 50% Sand (b)
Type of Electrode: Nickel Silver
Voltage Between Electrodes: 2.7 Volts
Sample Thickness at 0 Hours: 1.990 cm
Specific Gravity: 2.659

Date	Time	Hours	Current (ma)	Ht. of Rise (cm)	Comp. Dial Reading (in)
4/16/58	1500	0.0	23.5	0.0	.1198
	1515	.25	24.0	1.55	.1200
	1530	.50	21.5	3.05	.1201
	1545	.75	19.0	4.55	.1202
	1600	1.0	17.5	6.05	.1206
	1636	1.6	15.0	9.55	.1208
	1706	2.1	12.7	13.2	.1208
	1806	3.1	11.5	21.2	.1206
	1906	4.1	10.8	28.7	.1201
	2000	5.0	9.2	32.2	.1200
	2100	6.0	7.7	34.7	.1199
	2200	7.0	6.7	39.8	.1196
	2300	8.0	5.9	40.1*	.1190
	2400	9.0	5.1	41.3*	.1190
4/17/58	0100	10.0	4.6	43.4*	.1190
	1000	19.0	2.5	54.0*	.1190
	1200	21.0	2.4	54.9*	.1200
	1406	23.1	2.2	56.3	.1211
	1624	25.4	2.0	58.4	.1213
	1700	26.0	2.0	57.2*	.1216
	1900	28.0	1.9	59.6	.1215
	2000	29.0	1.9	57.3*	.1220
	2130	30.5	1.5	56.8	.1220
4/18/58	0848	41.8	1.4	56.5	.1224
	1500	48.0	1.2	54.1*	.1220

* Large gas bubble released just prior to these readings. Height of rise dropped approximately 2 cm.

TABLE 8

Raw Data

Sample: 20% Kaolin, 80% Sand
Type of Electrode: Silver Silver-Chloride
Voltage Between Electrodes: 2.7 Volts
Sample Thickness at 0 Hours: 2.270 cm
Specific Gravity: 2.696

Date	Time	Hours	Current (ma)	Ht. of Rise (cm)	Comp. Dial Reading (in)
4/5/58	1700	0.0	10.5	0.0	.1741
	1715	.25	8.1	0.2	.1741
	1730	.50	8.0	0.3	.1741
	1745	.75	7.8	0.35	.1742
	1800	1.0	7.6	0.5	.1742
	2000	3.0	6.3	0.9	.1740
	2200	5.0	5.0	1.2	.1732
4/6/58	0030	7.5	3.9	1.4	.1723
	0842	15.7	2.7	2.0	.1701
	1412	21.2	2.7	2.5	.1701
	1600	23.0	2.7	2.6	.1704
	2000	27.0	2.9	3.3	.1708
	2200	29.0	2.9	3.5	.1706
4/7/58	0848	39.8	3.0	4.9	.1692
	1100	42.0	3.0	5.2	.1692
	1300	44.0	3.1	5.8	.1692
	1800	49.0	3.1	6.1	.1691
	2018	51.3	3.1	6.6	.1690
	2100	52.0	3.2	6.4	.1689
	2200	53.0	3.2	6.5	.1688
4/8/58	0030	55.5	3.2	7.3	.1684
	0900	64.0	3.4	8.0	.1680
	1112	66.2	3.4	8.7	.1683
	1200	67.0	3.6	10.2	.1688
	1300	68.0	3.6	11.3	.1688
	1500	70.0	3.7	12.1	.1689
	1600	71.0	3.8	13.7	.1690
	1800	73.0	3.8	13.7	.1690
4/9/58	0112	80.2	3.9	19.3	.1686
	1200	91.0	4.6	38.7	.1688
	1500	94.0	4.8	46.4	.1692

TABLE 9

Raw Data

Sample: 10% Kaolin, 90% Sand
Type of Electrode: Silver Silver-Chloride
Voltage Between Electrodes: 2.7 Volts
Sample Thickness at 0 Hours: 2.108 cm
Specific Gravity: 2.703

Date	Time	Hours	Current (ma)	Ht. of Rise (cm)	Comp. Dial Reading (in)
4/22/58	1200	0.0	0.85	0	.1598
	1215	.25	0.85	0	.1596
	1230	.50	0.90	0	.1595
	1245	.75	1.0	0	.1594
	1300	1.0	1.1	0	.1592
	1400	2.0	1.3	0	.1589
	1700	5.0	1.0	0	.1572
	2200	10.0	.9	0	.1556
4/23/58	0900	21.0	.9	0	.1558
	1300	25.0	.9	0	.1741
	1700	29.0	.9	0	.1738
	2100	33.0	.9	0	.1739
4/24/58	0900	45.0	.9	0	.1778
	1200	48.0	.9	0	.1785
	1800	54.0	.9	0	.1805
4/25/58	0800	63.0	.9	0	.1848
	1500	75.0	.9	0	.1875

TABLE 10

Raw Data (pH Values)

Sample	Anode Side	Cathode Side
90/10	5.40*	5.28*
80/20#	- -	- -
70/30	6.30	5.60
50/50 (a)	7.20	6.70
50/50 (b)	6.20	10.30
20/80	6.65	5.60
10/90	5.93	6.67

* Values obtained after loss of sample and some intermixing of water.

\# No pH determinations made due to loss of sample and intermixing of water for several hours.

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